Remote Sensing in Support of Multilateral Environmental Agreements: What Have We Learned from Pilot Applications?

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1. Introduction

The rapid growth in the number of multilateral environmental agreements (MEAs, or "environmental treaties") since the 1972 Stockholm Conference on the Environment has been an encouraging sign of international commitment to protecting the environment. The proliferation of treaties, up from 140 in 1970 to over 350 today (IUCN 1998), has resulted in an attendant need for spatial data on the health of the Earth's biophysical systems, and for better understanding of the socio-economic processes and government policies that affect the environment. This information contributes to the design of improved policy instruments. Remotely sensed data are critical to understanding the Earth's physical and social systems and the interactions between the two. Although not the only tool for gathering such data, remote sensing complements ground-based methods in the following ways: it provides accurate, objective and comparable data; it provides information on ecological regions at widely-varying scales; and because it is sensed from space it can present a wide range of relevant data synoptically and without infringing national sovereignty. For some environmental agreements remote sensing may provide the only viable means of compliance verification because the phenomena being monitored occurs over large and inaccessible geographic areas.

This paper examines a number of pilot applications of remote sensing technology for the monitoring of environmental agreements. These applications include measurement of carbon stocks resulting from human-induced land-use change and forestry activities under Article 3 of the Kyoto Protocol; biodiversity assessment for the Convention on Biological Diversity; monitoring of forest resources for agreements on forest management and conservation; conservation of wetlands under the Ramsar Convention; monitoring of fisheries, oil spill and marine protected areas under various marine agreements; and analysis of trends and patterns of desertification under the Convention to Combat Desertification. The paper is primarily concerned with the technical specifications of remote sensing imagery as they relate to treaty-specific needs, and assumes some prior knowledge of remote sensing capabilities. Those desiring a primer on the principles of remote sensing should review the excellent materials available on-line (e.g., NASA's Observatorium at http://observe.ivv.nasa.gov/nasa/education/reference/main.html). Furthermore, issues related to the political feasibility of increasing the use of Earth Observation data in light of North-South disparities in access to these technologies and weaknesses in the treaty frameworks themselves are addressed elsewhere in the literature (see Uhlir 1995, CIESIN 2001, de Sherbinin *et al.* forthcoming).

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2. Remote Sensing Technology of Relevance to Environmental Treaties

The term “remote sensing” first emerged in the 1950s and refers to “the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation” (Lillesand and Kiefer, 1987). The history of remote sensing, however, dates back to as early as 1827 when Nicephore Niepce took the first picture of nature (Estes, 1999). Since then, the advancement of technology continued with the use of a captive balloon in 1858, pigeons in 1903, low altitude aircraft during World War-1, and high altitude aircraft in 1950s to take aerial photographs. The satellite remote sensing era began when TIROS-1, the first meteorological satellite, was launched in 1960. During the same period, high spatial resolution military intelligence satellites were launched by the United States (Corona) and the former USSR (KH), though these data have found their way into the public domain only recently. While, remote sensing data can be acquired from ground, aircraft, spacecraft and satellite sensors, our discussion in this paper is focused on the use of satellite data of relevance to MEAs.

Currently more than a dozen satellites are in orbit producing petabytes of data everyday. Platform, sensor and data characteristics of commercially available major satellites are presented in Appendix 1. Detailed descriptions of these satellites are beyond the scope of the paper, however, major characteristics of sensors can be summarized as follows:

- Spatial resolution of sensors ranges from 1 meter (e.g. IKONOS) to several kilometers (e.g. GOES);
- Satellite sensors commonly use visible to near-infrared, infrared and microwave portions of electromagnetic spectrum;
- Spectral resolution of satellite data ranges from single band (Radarsat) to multibands (e.g., MODIS with 36 bands);
- Temporal resolution (repeat time) varies from several times a day (e.g. Meteosat) to 35 days (ERS);
- The majority of satellites are sun synchronous and polar orbiting, crossing the equator at around 10 a.m. local time during their descending pass; and
- Digital data are available in both panchromatic (black and white) and multi-spectral modes.

Countries such as the USA, Canada, Japan, and France play key roles in designing, developing and launching satellites. More recently, developing countries (e.g., Brazil, China, and India) and private companies have developed and launched their own satellites. Private companies, such as Space Imaging and Ball Aerospace, are focused on marketing satellite data with a spatial resolution of 5 meters and higher. Developing countries on the other hand, are interested in launching their own satellites to fulfill their specific requirements and to become self-reliant. In this regard, small satellites are expected to become very popular.

With the launch of multiband/multisensor satellite data (e.g. TERRA), users now have multiple options to select spatial, spectral and temporal resolution according to their specific needs. The landmark decision of Landsat 7 to cut its price to $600 per scene and authorize redistribution of the data, once purchased, is good news in itself that is expected to trigger the use of satellite data for wider applications. Effective July 1, 2001, Landsat 5 data collected from 1984 to present no longer have restrictions on their use or redistribution.

More than two dozen satellites are scheduled to be launched between 2001 to 2003. The spatial resolution is expected to be as high as 0.7 meters (QuickBird-2). A list of major satellites designed primarily for land applications that are scheduled for launch in 2001-2003 is presented in Appendix 2. Both, presently available satellite data and those that will be available in the near future could potentially be used for deriving information relevant to MEAs.

At least four workshops have focused attention on the use of remote sensing technology to derive information relevant to MEAs. The International Society of Photogrammetry and Remote Sensing (ISPRS) organized a workshop in Ann Arbor, Michigan, USA in October 1999 to discuss the available and future technology of remote sensing for providing information related to Kyoto Protocol. Similarly, the African Association of Remote Sensing of the Environment in its 3rd symposium held in Cape Town, South Africa in March 2000 discussed the possibility of using remote sensing data to support environmental treaties and agreements. More recently, a two-day workshop was organized by Socioeconomic Data and Application Center of CIESIN, Columbia University in December, 2000 in Washington D.C. to specifically address remote sensing applications for MEAs and featured thematic sessions focusing on biodiversity and ecosystem management, atmospheric change and climate change, and institutional and remote sensing instrument design (CIESIN, 2001). Finally, a workshop held on the auspices of American Institute of Aeronautics and Astronautics (AIAA) in Seville, Spain from 11-15 March 2001 discussed about the contribution of space systems to the development and implementation of MEAs.

Kline and Raustiala (2000) highlighted that remotely sensed data can be used for various aspects of MEAs including MEA negotiation, implementation review, and compliance and dispute resolution and reporting. The benefit of using satellite data is that they provide objective, unbiased, and transparent data sources in a near real time basis. Additionally, satellite data can be acquired repeatedly covering a large area (synoptic coverage).

Although, the existing satellites were not designed to meet the information requirements of environmental treaties, they can be used to generate key information necessary for developing and implementing MEAs. There are several initiatives that are explicitly seeking to apply remote sensing data to the needs of environmental treaties. Among the more ambitious are the European Commission’s Global Monitoring for Environment and Security (GMES), the Meso-American Biological Corridor, and the Millennium Ecosystem Assessment, which are briefly described.

GMES is an effort of the EC to coordinate and expand the use of remote sensing in three primary areas: environmental treaties, natural disasters (especially floods and forest fires), and a third area grouping together environmental stresses, population pressures and humanitarian aid. For environmental treaties, GMES looks at applications tied to specific treaty provisions, such as land-based carbon sinks and emissions under the Kyoto Protocol. GMES began in 1998 as a technically driven initiative by the European space agencies, but has evolved since then into a politically accepted concept. What the GMES has succeeded in doing is uniting the needs of various users in the EU member governments, thereby providing a useful forum for interaction between the EC, government agencies involved in disaster preparedness or environmental negotiations, and the European space agencies.

As part of GMES, the European Space Agency put out a request for proposals in 2001 under the banner of Treaty Enforcement Services Using Earth Observation (TESEO), the focus of which is to fund research supporting remote sensing applications specific to the Ramsar Convention on Wetlands, the Kyoto Protocol of the UN Framework Convention on Climate Change, the UN Convention to Combat Desertification, and the Convention for the Prevention of Maritime

Pollution from Ships (MARPOL). The ESA seeks to develop a prototype aimed at demonstrating the capabilities of existing and future EO technology to support end-users – e.g., treaty secretariats and contracting parties – in the implementation of the these treaties.

The Meso-American Biological Corridor is an excellent example of remote sensing applications in support of a regional environmental treaty. The biological corridor is a planned combination of protected areas and managed landscapes that forms a continuous wildlife migration route from Panama to the Mexican border. Owing to its position between North and South America, Central America possesses significant biodiversity, yet the region has suffered from armed conflicts, and the ecosystems are under stress from population growth, legal and illegal logging, slash and burn agriculture, and cattle ranching. As the region's major environmental initiative, the Corridor combines conservation and sustainable use of biodiversity within the framework of sustainable economic development.

The Central American Commission for Environment and Development (CCAD) approached NASA for remote sensing expertise in support of the corridor agreement, and in 1998 an MOU was signed. The project includes the following: development of maps classifying the land cover of the Central American isthmus; support for the development of CCAD's environmental data and information system; technical assistance to improve estimates of carbon sequestration in particular areas within the corridor; and regional capacity building. NASA's U.S. partners in this effort are the University of Maine and the Jet Propulsion Laboratory. The project has utilized a mosaic of Japanese JERS radar data as the baseline for mapping, in conjunction with digital elevation data and optical remote sensing imagery for nine intensive study areas. Field work is being undertaken by Central American counterparts to validate the data. So far the project has developed a number of important data sets and a web site for data dissemination, and it has carried out three training workshops for capacity building.

The Millennium Ecosystem Assessment (MA) is the latest in a series of global integrated assessments. The MA seeks to improve the management of ecosystems and their contribution to human development by helping to bring the best available information and knowledge on ecosystem goods and services to bear on policy and management decisions. The MA consists of a global scientific assessment as well as a number of smaller, more focused regional, national, and local assessments. The primary users of MA results include the international ecosystem-related conventions – the CBD, CCD, and Ramsar – and their contracting parties, though as with other assessments, there will be a much wider audience of UN and non-governmental agencies, many of which will attune their policies and programs to the assessment results.

Because of the "location-specific" nature of the assessment, the MA depends heavily on characterizing ecosystems at particular places and times. In particular, for terrestrial ecosystems, information on land cover and land use, and socio-economic data about the people living on the land are fundamental. This provides the basic framework needed to examine the benefits people are obtaining from ecosystem goods and services and how changes in those services may affect livelihoods. Remote sensing data will be integral to this effort. In conjunction with the NASA's Global Land Cover data, the MA seeks to develop a global coverage of processed remote sensing images for the year 2000. This effort will classify ecosystem type and land use at particular locations using continuous variables (e.g., percent tree cover, percent grass cover, etc.), rather than categorical variables (e.g., forest/non-forest), wherever possible.

Not all the information needed by convention secretariats can be measured by satellite data and there are limitations in using this technology. The future, however, is promising especially given the availability of various types of satellite data that are either launched or planned to be launched in the near future. The recent development in hardware, software and information technology is also making this technology accessible to a larger audience, particularly in developing countries. Remote sensing has great potential to provide information relevant to environmental treaties. However, the technology is not yet fully exploited.

3. Applications of Remote Sensing to Environmental Treaties

This section provides examples of applications of remote sensing in four domains: Biodiversity-related agreements, the Kyoto Protocol, the Desertification Convention, and Marine conventions.

3.1 – Biodiversity-related Agreements

Satellite derived information may be relevant to the needs of biodiversity related treaties such as the Convention on Biological Diversity (CBD), the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the Convention on Migratory Species of Wild Animals (CMS), the Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar) and the Convention Concerning the Protection of the World Cultural and Natural Heritage (WHC). A brief summary of the type of information that can be derived from remote sensing and the potentially relevant biodiversity treaties are found in Table 1.

There are few examples of remote sensing applications specifically designed to meet the information requirements of biodiversity related treaties. However, several relevant projects and research studies have generated information of relevance to biodiversity related treaties. Selected examples of these applications are presented below.

It should be noted that beyond strictly technical applications, remote sensing imagery can influence high-level political decisions that are directly relevant to treaty implementation. For example, the 1990 establishment of the 4-million biosphere reserve straddling the border between Mexico and Guatemala "was in part due to evidence of tropical forest destruction gained through satellite data" (Kline and Raustiala 2000). The Mexican side was largely deforested while the Guatemalan side held largely intact forest cover. The stark contrast at the border, clearly visible in a Landsat image, catalyzed the first meetings in decades between the Mexican and Guatemalan presidents to discuss border land management. The decision to set up the Meso-American Biological Corridor is partly related to these same events. The image demonstrated the potential for remote sensing to monitor large-scale changes in the regional environment and helped create a climate in which regional environmental planning is possible.

3.1.1 – Habitat Loss and Fragmentation

Habitat loss and fragmentation are the most important causes of biodiversity loss (Foin et al., 1998). These variables can be monitored relatively effectively using satellite imageries. Riitters et al. (2000) used NOAA AVHRR 1-km data to analyze forest fragmentation around the world. Six categories of fragmentation namely interior, perforated, edge, transitional, patch, and undetermined were identified. The study found significant differences in fragmentation among continents. A similar study conducted by Skole and Tucker (1993) using time-series Landsat data from 1978 to 1988 to quantify deforestation and fragmentation of Brazilian Amazon Basin found that tropical forest habitat loss and biodiversity loss during that period were directly related.

Table 1. Summary of main information requirements that can be derived from satellite data

Satellite Sensor	Main information required for treaties that can be derived from satellite data	Related Treaties
Coarse Spatial Resolutoin (1 km – 16 km)	Status & change of forest ecosystems	CBD
	Status & change of habitat types	CBD, Ramsar, WHC
	Habitat fragmentation/destruction	CBD, CITES, CMS, Ramsar, WHC
	Land Cover	CBD, Ramsar
	Forest Fire	CBD, CITES, CMS, Ramsar, WHC
Medium Spatial Resolution (30 m – 500 m)	Status & change of forest ecosystems	CBD
	Status & change of habitat types	CBD, Ramsar, WHC
	Monitoring conservation & protection status	CBD, CITES, CMS, Ramsar
	Habitat range and distribution	CBD, CITES, CMS, Ramsar, WHC
	Habitat fragmentation/destruction	CBD, CITES, CMS, Ramsar, WHC
	Mapping invasive/exotic species	CBD, CMS, Ramsar
	Land Use/land Cover	CBD, Ramsar
	Evaluating the presence of corridors	CBD
	Species distribution	CBD, CITES, CMS, Ramsar
	Forest Fire	CBD, CITES, CMS, Ramsar, WHC
High Spatial Resolution (1 m – 30 m)	Status & change of forest ecosystems	CBD
	Status & change of habitat types	CBD, Ramsar, WHC
	Monitoring conservation & protection effectiveness	CBD, CITES, CMS, Ramsar
	Habitat range and distribution	CBD, CITES, CMS, Ramsar, WHC
	Critical habitat delineation	CBD, CITES, CMS, Ramsar, WHC
	Migration routes	CMS, Ramsar
	Habitat fragmentation/destruction	CBD, CITES, CMS, Ramsar, WHC
	Mapping invasive/exotic species	CBD, CMS, Ramsar
	Evaluating the presence of corridors	CBD
	Species distribution	CBD, CITES, CMS, Ramsar
	Biomass	CBD
	Land Use/Land Cover	CBD, Ramsar
	Leaf Area Index	CBD
	Net Primary Production	CBD, Ramsar
	Road Density	CBD, CITES, Ramsar
	Forest Fire	CBD, CITES, CMS, Ramsar, WHC
	Logging	CBD, CITES, CMS, Ramsar, WHC

In southern New England (USA), local level spatial patterns and rates of forest fragmentation were assessed using Landsat data from 1973 and 1988. One of the major finding of the study was that forest fragmentation is occurring over large regions within the eastern United States (Vogelmann 1995). Similarly, AVHRR and Landsat data were used to investigate forest fragmentation in Oregon, USA. The resulting map showed the highest levels of forest fragmentation in the Oregon Coast Range and the lowest fragmentation in the southern Cascade Mountains (Ripple 1994). Such, information on habitat loss and fragmentation could be useful to the Convention on Biological Diversity particularly to safeguard in-situ conservation of ecosystems and natural habitats through identification and monitoring of such ecosystems and habitats (CBD, Anex I, Paragraph 1 and Preamble).

Richard Podolsky developed the software application Diversidad that computes diversity, maximum diversity and percent of maximum diversity from satellite imagery (e.g. Landsat and SPOT) based on the work of the Shannon and Weaver. This tool is useful for identifying areas of potentially high biodiversity based on the spectral signature. This can help target resources for field inventories.

3.1.2 – Habitat Suitability Mapping

Another popular application of satellite data is as input to wildlife habitat suitability maps. Scheierl and Meyer (1976), Hagen and Meyer (1977) and Aronoff (1982) used satellite data to evaluate the suitability of habitats for waterfowl, black bear and moose. A common approach for such an effort is to prepare vegetation maps using satellite data and to evaluate habitat preference and conditions of wildlife species based on field information.

Novo and Shimabukuro (1997) used Landsat TM data to identify and map Amazon habitats into six classes: (i) clear/mixed water, (ii) turbid water, (iii) flooded non-forest, (iv) flooded forest, (v) human settlements and (vi) aquatic vegetation. Similarly, JERS-1 SAR data was used to prepare a land cover/land use map to support research along the Mesoamerican Biological Corridor. Once habitat types are identified, the next step is to relate these habitat types with wildlife distribution information obtained from field survey. This is often accomplished using species-habitat association models.

Habitat suitability models are usually derived by combining several types of ecosystem data, including geology, soils, vegetation, elevation and slope. Satellite data derived variables are then included in ecosystem-scale forest biodiversity models (Innes and Koch, 1998). Likewise, Debinski et al.(1999) used Landsat TM data and GIS to categorize habitats and to determine the relationship between these and species distribution patterns. A strong correlation between high species richness of plants, birds, and butterflies was found with the mesic meadows (one of the six habitats). Moreover, 20-30% of animal taxa and 65-100% of the dominant plant species were significantly correlated with one or more remotely sensed derived habitats.

Tamura and Higuchi (2000), used Landsat TM data to investigate the habitat conditions of two migratory birds – red crowned cranes and oriental white storks – living in East Asian wetlands. By combining satellite tracking and Landsat TM satellite data they analyzed the relationship between ground conditions and habitation patterns of these species. One important outcome of this study was the identification of habitat preferences for these two birds during their migration between Russia and China.

Satellite data can also be used to locate critical habitat types of wildlife species. A study conducted in Kruger national Park (KNP) in South Africa using Landsat 7 ETM+ found that the ecotone between wetlands and savanna uplands is the critical grazing zone for antelope. This information will assist managers to better manage antelope habitat. Habitat suitable for relocation of wildlife species can also be derived from satellite data. Landsat data was used to locate a habitat suitable for the re-introduction of indigenous species of Australia, rufous hare-wallabies (*Lagorchestes hirsutus*). Three potential sites were identified and verified from the field survey. This technique can be used for rapid assessment of rare animal habitat distributions over large areas (Saxon, 1983).

According to the CBD, habitat suitability mapping would help ‘rehabilitate and restore degraded ecosystems and promote the recovery of threatened species, inter alia, through the development and implementation of plans or other management strategies’ (Article 8, Paragraph f). This information would also help ‘develop, where necessary, guidelines for the selection, establishment and management of protected areas’ (Article 8, Paragraph b).

3.1.3 – Wetlands Mapping and Monitoring

Wetlands mapping and monitoring is another typical application of satellite data. NOAA AVHRR and Landsat TM data were used to map water and plant distributions in two Ramsar sites - Khingan Nature Reserve and Ganukan Landscape Refuge- in the Russian Far East into three categories, the wettest part with sedges and reeds, the modestly wet part with sedges and grasses and the dry part with various kids of grasses. Wetlands types were then overlaid with migratory route of red crowned cranes and oriental white storks to identify their preferable habitat type (Tamura and Higuchi, 2000). This information could be useful to the Convention on the Conservation of Migratory Species of Wild Animals (CMS) to undertake “appropriate and necessary steps to conserve migratory species and their habitat” which is highlighted in Article II of the convention. Similarly, Landsat TM data was used to prepare a land use map of tropical forests and wetlands of Sango Bay, Uganda, which was then combined with field surveys data on plants and animals to prepare a biodiversity map. This biodiversity map was then used for conservation and planning. Thus, remotely sensed data could be useful to;

(1) Describe the range and migration route of the migratory species (CMS, Article V, Section 4.b)
(2) Periodic review of the conservation status of the migratory species concerned and the identification of the factors which may be harmful to that status (CMS, Article V, Section 5.a)
(3) Review and assess the conservation status of migratory species and their habitat (CMS, Article VII, Section 5) and
(4) Inform to the Secretariat, “at the earliest possible time if the ecological character of any wetland in its territory and included in the list has changes, is changing or likely to change as the result of technological developments, pollution or other human interference (Ramsar, Article 3.2).

3.1.4 – Identifying and Monitoring Threats

One of the information requirements of CBD is to identify and evaluate the underlying causes of biodiversity loss. To identify and evaluate the potential threat of biodiversity loss, time series satellite data from 1986 to 1997 was used in the Maya Biosphere Reserve in Northern Guatemala to derive forest cover change maps to monitor agricultural expansion (Sader et al., 2001). Similarly, IRS data was used to study land cover, vegetation types, physiography/land forms and human interventions at multiple spatial scales in Madhav National Park (M.P.) and Balphakram National Park (Meghalaya) of India (ISRO 1998).

The devastating Indonesian wildfire in 1997 threatened wildlife and wildlife habitat. NOAA AVHRR data was used to identify forest fire ‘hot spot’ areas. By overlaying these ‘hot spot’ areas with protected areas maps, the World Conservation Monitoring Centre (WCMC) identified a list of protected areas threatened by forest fire. In the same way, road density could potentially be derived from RS data as an indicator of human disturbance.

Lambin and Mertens (2001) used time series satellite data of Landsat and SPOT to monitor the abrupt and periodic shifts in a marsh location and their impact on biodiversity. These shifts in swamp location changed habitat location and lead to major disturbances for wildlife species. Similarly, SPOT XS and panchromatic data were used to evaluate and monitor the impact of encroaching agricultural and urban development in Florida’s Loxahatchee National Wildlife Refugee.

3.2 – Kyoto Protocol

In July 2001 the Contracting Parties of the UN Framework Convention on Climate Change, with the exception of the United States, reached agreement on a plan for implementing the Kyoto Protocol. The agreement allowed the possibility for countries to claim forest carbon sinks as an offset to their greenhouse gas emissions, and, through the Clean Development Mechanism, to purchase carbon offsets by investing in aforestation and reforestation projects in non-Annex 1 countries.[2] A number of developing countries have been exploring the possibilities for entering the carbon market by protecting tropical forests or reforesting large areas.

Experts at a December 2000 workshop on remote sensing and environmental treaties (CIESIN 2000) determined that there are several systems currently in place in either operational or experimental modes that could meet the data needs of the Kyoto Protocol. First, there are coarse, moderate and fine resolution passive optical systems that are sensitive to surface chemistry (via pigmentation) and this data can be used to infer other surface conditions (i.e., land cover class). There are also experimental airborne LIDAR (Light Detection and Ranging) systems that can measure canopy height; the most advanced systems record the full wave return and can also provide information on surface height and the vertical distribution of vegetative material. In addition, there are microwave (radar) satellite systems that can measure moisture and structure (for above ground biomass). However, LIDAR and radar systems were not on satellites for the Kyoto baseline period of 1990. A number of satellite radar systems have been put into service by the international community (notably Japan, Europe and Canada) during the 1990s, though none of these are particularly well-suited for collecting data that can be used to estimate above-ground biomass on a global basis, nor have they been tasked to do so.

Challenges identified during this workshop include the potential cost of coordination, standardization and conversion of optical, radar and LIDAR data through common empirical models to yield estimates of carbon sequestered. Integration of these data requires accurate digital elevation models of topography that today are only locally available (though this should be remedied over the next year given the recent success of the NASA/NIMA Shuttle Radar Topography Mission). It must be noted that in most cases, remote sensing does not provide a single source solution to information needs; rather it serves to extend an ongoing and healthy program of *in situ* observations. Within this context, the promise of remote sensing is to allow the development of more robust and efficient ground sampling strategies and to subsequently extrapolate from such *in situ* measurements in both space and time. More information on technical specification of systems needed for the Kyoto Protocol can be found in Rosenqvist *et al.* (1999).

There are currently pilot efforts to monitor forest carbon sequestration using remote sensing in Costa Rica and Bolivia. One such effort is taking place in the Noel Kempff Mercado National Park in northeastern Bolivia. Noel Kempff spans over 3.7 million acres (1.5 m. hectares) in one of the most biologically diverse areas in the world. A project, developed by The Nature Conservancy, the Brazilian Government and financed by a number of utility companies, has plans to sequester 7-10 millions tons of carbon over a 30 year period. As part of the justification, project proponents needed to prove that the area encompassed by the project would otherwise have been deforested; in other words, by protecting the forest, the project is yielding additional carbon sequestration benefits that would not otherwise have accrued. One of the primary

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[2] Annex 1 parties to the UN Framework Convention on Climate Change are industrialized countries, the major emitters of greenhouse gases. Non-Annex 1 parties are developing countries with lower emissions.

technical hurdles to the use of carbon sinks in Kyoto is the accurate measurement of above-ground biomass. For this project, remote sensing was used initially to develop a vegetation stratification map of the area, and work is ongoing to investigate the application of high resolution aerial videography and laser altimetry for annual monitoring of selected areas. Using an extensive network of monitoring plots and the dual camera aerial videography, the monitoring and verification program quantifies with a high degree of precision how much carbon existed in the project area prior to commencement of the project, the carbon losses avoided, and how much carbon is captured as a result of the project. On the basis of this experimentation, methodologies will be developed that can be applied to other forest carbon sequestration projects at lower costs (Noell Kempff 2001).

For Kyoto, there is a need for a number of GHG measurements that can be obtained wholly or partly via remote sensing. These include methane and nitrous oxide emissions, which are related to land cover features such as inundated areas (rice paddies), soil moisture, and temperature. There is an interest in land cover type, height, and above ground biomass (woody vegetation). Existing RS technology may be more readily used for estimating carbon sequestration on agricultural lands than in forested areas because tillage practices and crop types can be identified through optical imagery alone.

3.3 – Desertification

Remote sensing imagery is vital for the understanding of land cover change, and thus forms an essential element of any effort to track land degradation and desertification trends. Remote sensing also forms a critical element in early warning systems for drought and famine. Many national reports to the UN Convention to Combat Desertification now feature estimates of land degradation based on remote sensing data.

An innovative study by Tappan *et al.* (2000) analyzes long-term land cover changes in the Peanut Basin of Senegal utilizing a series of data, beginning with Corona and Argon reconnaissance satellite images from the 1960s, and proceeding to Landsat TM images of the early 1990s. Their study showed a dramatic decline in the bush-fallow system over time. Agricultural land area doubled, where as bushlands declined by 95 percent, and woodlands declined by 87 percent. The authors conclude that population change, policies encouraging agricultural expansion, rainfall declines and soil and forest mismanagement have led to increasing land degradation and loss of common pool resources in the region.

Responding to commonly cited figures regarding the expansion of desert areas, Tucker *et al*. (1991) utilized the normalized difference vegetation index (NDVI) derived from AVHRR data to study the growth and contraction of the Sahara desert over the 1980s. They found that the position of the 200 mm isoline (as measured by NDVI) in 1990 was about 130 km south of its position in 1980, and that the area defined as desert expanded a maximum of 15% during the 1984 drought. Their data provide important baselines for future studies of desertification, and highlighted the significant interannual variability in the location of the southern margins of the desert. Similarly, the Space Applications Institute in Ispra, Italy has examined the north and southward migration of high albedo areas using METEOSAT data. These areas of high reflectance are strongly correlated with absence of vegetation and low soil moisture (GMES 2000). Such products are useful for national reporting to the CCD secretariat, and given that they are derived from meteorological satellites with high temporal resolution and coarse spatial resolution, they do not require intensive processing and data products can be furnished in near real time for drought and famine preparedness.

Mouat and Lancaster (2000) describe a decision support tool utilizing ASTER and MODIS data in South Africa and Namibia. The MODIS data, together with aerial photography and early date Landsat data, are used to generate a desertification potential profile. GIS models will then be developed to illustrate the impact of different future land use options for study sites in order to focus management and remediation efforts on areas most likely to benefit from future intervention. An innovation is the involvement of stakeholders in an integrated assessment approach in which they express their preferences concerning future management practices.

3.4 – Marine Applications

The primary marine applications of remote sensing include measurements of sea-surface temperature using infrared radiometers, sea-surface elevation by altimeters, ocean color (and thereby primary productivity) by spectrometers, and surface roughness by active and passive microwave (radar) systems (Johannessen and Sandven 2000). These in turn relate to various parameters of interest to marine treaties. The principal advantage of remote sensing for marine monitoring is the large areas that can be covered on a continual basis – far more than could be covered by marine research vessels.

The Global Ocean Observing System (GOOS) is the primary international vehicle for efforts to harness remote sensing for the monitoring of marine ecosystem health. Agenda 21 called for efforts to "pursue the protection and sustainable development of the marine and coastal environment and its resources," and nations agreed to collect, analyze and distribute data and information and to cooperate through the GOOS (NAS 1997). According to their web site, "GOOS will provide accurate descriptions of the present state of the oceans, including living resources; continuous forecasts of the future conditions of the sea for as far ahead as possible; and the basis for forecasts of climate change."

3.4.1 – Marine Fisheries and Endangered Species Monitoring

Satellite images of both ocean color and temperature have been used for identification of particularly promising fishing grounds. For example, IKONOS imagery is being used to identify areas in which the ocean is particularly rich in phytoplankton. Using a software package by Orbital Imaging, fishing fleets can calculate the plankton's movements based on weather and ocean conditions. Because larger fish, like tuna, are likely to be near the plankton, such a tool can direct fishing fleets to abundant fishing grounds, adding significantly to their profitability (Feder 2001). Such tools could be turned around in the service of enforcement; once you know where the fish are, you know where the fishermen are likely to congregate, which can help law enforcement agencies target monitoring efforts related to fisheries agreements. The National Marine Fisheries Service of NOAA has used ocean temperature data, collectible by AVHRR sensors, for predictive purposes as well (Roffer 2001).

Satellite tracking is being actively used in the enforcement of certain fishing zones, for example under the Northwest Atlantic Fisheries Organization. A Canadian firm, IOSAT, developed an experimental application using Radarsat imagery to identify vessels operating in the restricted fishing zones at trawling speeds (Herman 2001). Global Positioning System (GPS) technologies are also used in tracking movements of endangered or over-fished marine species (e.g., Block *et al.*, 1998). These applications could potentially be of use under CITES should the treaty move in the direction of extending its mandate, which currently focuses primarily on trade prohibitions, to preventing the illegal capture of endangered species. A study examined the migratory routes of green turtles on the Atlantic coast of Brazil. GPS tracking devices were attached to turtles, and their migration routes were compared with sea-surface temperature data derived from AVHRR to determine if green turtles followed specific isotherms in their migrations. Though the research found that turtles do not follow specific isotherms, for other species remote sensing data might provide information about likely migration routes (Hays *et al.*, 2001).

3.4.2 – Oil Spill Monitoring

The Bonn Agreement, officially known as The Agreement for Cooperation in Dealing with Pollution of the North Sea by Oil and Other Harmful Substances (1983), is an example of a rigorously enforced agreement within the context of the International Convention for the Prevention of Pollution from Ships (MARPOL). Under the Bonn Agreement, monitoring procedures have been set up to track oil spills to the ships of origin. Because oil slicks change the surface roughness of water bodies under the windy conditions that generally prevail on high seas, and this registers as changes in backscatter on radar instruments, SAR images have proven useful for spill monitoring (Jones 2001). However, radar images generally give an unacceptable number of false positives, so the technology is only applicable as a surveillance tool in conjunction with IR and UV sensors, used for reconnaissance and confirmation of potential slicks. Under the Bonn Agreement, photographic evidence is still required in order to bring a ship's owner to prosecution. The advantage of SAR is that it can cover a huge expanse of ocean, and its relatively low rates of false negatives means that limited surveillance resources (generally aircraft equipped with passive IR and UV sensors and photographic equipment) can be targeted to areas that are definitely suspected of having experienced a spill.

By 2002, the International Maritime Organization will require vessel tracking transponders on all commercial ships; this could permit back-tracking of vessels to the scene of an oil slick several hours after the initial incident occurred (Lankester 2000). However, the potential for a fully automated system is some ways off. Colliander and Fast (1999) note in their own treatment of the subject that the legal systems in most countries still require the testimony of a person, such as a coastguard officer, in addition to remote sensing images and photographs. They also discuss the many ways in which remote sensing can be applied in management of a oil slick response efforts.

3.4.3 – Coral Reefs

Coral reefs are the tropical rainforests of marine ecology – they are rich in biodiversity, and provide excellent habitat for fish breeding (Knight *et al.* 1997). They are also very much threatened by human activities, including sedimentation, dynamiting, coral bleaching from increased temperatures, and submerging from sea-level rise. The *Status of Coral Reefs of the World 2000* report states that 27 percent of the world's reefs have been lost (AIMS 2000). In a recognition of the importance of improved information for reef conservation, a number of efforts are under way to use remote sensing imagery for monitoring and conservation.

The Coral Reef Early Warning System (CREWS) developed by NOAA monitors coral bleaching in the Florida Keys and the Great Barrier Reef of Australia. ReefBase is a global database on coral reefs and their resources that serves as the official database of the Global Coral Reef Monitoring Network. Objectives include the investigation, definition, and analysis of coral reef ecosystem health at global, regional, and national levels. ReefBase managers are currently looking at processing requirements for the inclusion of remotely sensed data in the database (McManus 1997).

Knight *et al.* report that most applications of remote sensing to coral reefs are confined to identification of reef configuration in shallow water. There some technical difficulties in compensating for the attenuation of radiance through the water column, as well as incomplete understanding about the spectral characteristics of specific coral and algae species. Water quality conditions also complicate reef identification. However, using SPOT imagery they have been able to determine the spectral response of corals at up to 10m depth in tropical waters, provided there are optical measurements of the water properties from which to measure the diffuse volume attenuation.

4. Conclusion

This paper outlines a number of pilot applications of remote sensing to the needs of MEAs. It is clear that there are many more environmentally relevant remote sensing research efforts than could be described in this paper. What we have attempted to do is focus on those efforts of greatest relevance and promise for the development, implementation or monitoring of environmental agreements.

A number of factors may affect the adoption of remote sensing data for treaty negotiation, compliance monitoring, national reporting, and monitoring of environmental trends of interest to MEAs. Issues, problems and constraints include the following:

- Data gaps – availability of right data at the right time.
- Cloud cover – particularly for biodiversity and land cover applications in the tropics.
- Lack of systematic archiving of remote sensing images.
- Regional disparities in data access, and in the skills needed to interpret imagery.
- Data costs, which are still significant, particularly for high-resolution imagery.
- Costs of ground-truthing – remote sensing is seldom sufficient in its own right, but needs to be combined with selective ground-truthing.
- Sovereignty concerns.
- Most applications are still experimental, and costs of scaling up are significant.
- Current lack of an international institution to coordinate among space agencies, value-added companies, and MEAs for technology and applications development.

On the latter, there are however a number of promising candidate organizations that could play this role, such as the Committee for Earth Observation (CEOS) or the Integrated Global Observing Strategy (IGOS).

Opportunities for expanded use of remote sensing for environmental treaties include the following:

- Radar technology – use of radar data in conjunction with optical remote sensing data provides complimentary information. Radar data provides information in areas affected by persistent cloud cover.
- Data availability is increasing – Wide variety of satellite data in multiple resolution are becoming available.
- Low cost of Landsat 7 data – Landsat-7 data is now available at a nominal cost of US$600 per scene.
- Private sector involvement – private companies are launching and involved in the interpretation of satellite imageries.

- Increasing developing country involvement – Increasingly, developing countries such as Brazil, China, and South Korea are launching their own satellites.

Remote sensing technology and the tremendous contemporary expansion of multilateral environmental treaties grew out of separate but parallel developments in the 1960s and 70s. For most of this period scientists and decision-makers on both sides had little contact; remote sensing scientists were unaware of the data needs of the treaty community, and treaty staff and contracting parties were often ignorant of what remote sensing technologies were available. As described in section 2, several recent workshops have been organized expressly to foster dialog, and gradually the gap is being bridged. Many challenges still exist in the technical, institutional, and political domains, but there are signs, such as the organization of GMES in Europe, that the critical integration of remote sensing technology and international environment policy is beginning to take place.

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Appendix 1. Platform, sensor and data characteristics of major satellite systems

Satellite	Instrument	Spatial Resolution (meters, at nadir)		Swath (km)	Repeat Cycle (day)	Type	Descending Pass	Altitude (km)	Period (Minutes)	Archive/ Launch year	Country
		PAN/ SAR	XS								
IKONOS	IKONOS	1	4	300	11	SS	10:30 a.m.	681		1999	USA
Landsat 7	ETM+	15	30	185	16	SS	10.00 a.m.	705	100	1999	USA
SPOT-5	2xHRV-IR	10	20	60	3	SS	10.30 a.m.	832	101.4	1986	France
	Vegetation		1000	2200	1		10:30 a.m.	832	101.4	1998	France/EU
IRS-1D	PAN	5.8		70	5-24	SS	10.30 a.m.	905	101.35	1997	India
	LISS 3		23, 70	145	24		10.30 a.m.	905	101.35	1997	India
	WiFS		160	774	5-24		10.30 a.m.	905	101.35	1997	India
CBERS	CCD	20	20	120	3-26	SS	10.30 a.m.	778	100.26	1999	China/ Brazil
	IR-MSS	80	80	120	26		10.30 a.m.	778	100.26	1999	China/ Brazil
	WFI		260	900	3-5		10.30 a.m.	778	100.26	1999	China/ Brazil
TERRA	ASTER		15, 20, 90	60	16	SS	10.30 a.m.	705	90	1999	USA/ Japan
	CERES		20 k.m.								
	MODIS		250,500,1000	2300	2						
	MOPIT										
	MISR		240,480,960,1 900	370-408	2-9						
RESURS	MSU-SK		170,600	600	2-4	SS	10.30 a.m.	678	98	1994	Russia
NOAA	AVHRR		1100	3000	0.5	SS	10.30 a.m.	833	102	1978	USA
MOS	MESSR		50	100	17	SS	10-11:00 a.m.	909	103	1990	Japan
	VTIR		900,2700	1500							
	MSR		23,32	317 k.m.							
SeaStar	SEAWIFS		1.1, 4.5 km	2801, 1501	1	SS	12:20 p.m.	705	99	1997	USA
GOES	Imager		1000, 4000	Hemisphere	0.2	GS				1994	USA
	Sounder		10000		0.2						
Meteosat	VISSR	2500	5000	Hemisphere	0.02	SS	-	850	100	1977	Europe
TRMM	PR	4000		220	0.067	NSS	Variable	350	91.5	1997	USA/Japan
	TMI	5-10 km		760							
ERS	SAR	35		100	30	SS	10.15 a.m.	785	100	1991	ESA
Radarsat	SAR	24		50-500	8-100	SS	06:00 a.m.	798	100	1995	Canada

Appendix 2. Satellites planned to be launched for 2001-2003

Year	Sensor	Country	Spatial Resolution
2001	OrbView-3	USA	1 m, 4 m
	OrbView-3	USA	1 m, 4 m
	CBERS-2	China/Brazil	20 m, 80 m, 260 m
	ADEOS-2	Japan	250 m, 1 km
	IRS-P6	India	10 m
	QuickBird-2	USA	0.6 m, 2.8 m
	ARIES-1	Australia	10, 30 m
	NOAA-M	USA	1 km
	Envisat-1	Europe	30 –1000 m
	VCL	USA	25 m x 25 m x 1 m
	EROS-A2	USA/Israel	0.82 m
2002	MODIS – AQUA	USA	250 m, 500 m, 1 km
	SPOT-5	France	5 m, 20 m
	IRS-P5	India	2.5 m
	EagleEye	Germany	5.7 m
2003	CBERS-3	China/Brazil	5 – 260 m
	CBERS-4	China/Brazil	5 – 260 m
	ALOS	Japan	2.5 m, 10 m
	IRS-2A	India	1 m
	NOAA-N	USA	1 km
	IRS-P7	India	6 m, 23.5 m, 80 m
	IRS-P8	India	6 m, 23.5 m, 80 m
	Radarsat-2	Canada	3 m