# Remote Sensing in Support of Ecosystem Management Treaties and Transboundary Conservation

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**The Project Team**

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# FORWARD

The genesis of this report and the broader project of which it is a part was a workshop co-organized by CIESIN, IUCN and MEDIAS-France and hosted by the Woodrow Wilson International Center in December 2000, entitled "Remote Sensing and Environmental Treaties: Building More Effective Linkages.[1] Support for the workshop was provided by the NASA-funded Socioeconomic Data and Applications Center (SEDAC), which is managed by CIESIN. The workshop engaged 67 experts from the international policy and remote sensing communities to examine current and potential applications of remote sensing to two broad areas, ecosystem management and climate change, and to discuss the political and technical feasibility of developing operational programs to monitor treaties from space. We were honored to have the then Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs (OES), Mr. David B. Sandalow, make a keynote speech on the work that OES was undertaking to facilitate the use of remote sensing in international environmental affairs. OES subsequently provided the funds for the project on Remote Sensing Technologies for Ecosystem Management Treaties.

Since that December 2000 workshop there have been a number of international meetings on the subject of remote sensing applications for treaties, and several large initiatives have been launched. These include the Millennium Ecosystem Assessment and the European Space Agency's Treaty Enforcement and Satellite Earth Observations, which are of direct relevance to the themes addressed in this report. Interest in transboundary conservation, and professional networks in that area, have also seen a rapid increase. Developments in the fields of international environmental governance and remote sensing technology are fast paced. This report necessarily represents a snap-shot in time, yet it is my hope that it illuminates both the utility and the challenges of applying remote sensing to the crucial areas of biodiversity conservation and ecosystem management. Comments are welcome, and should be directed to me via the e-mail address below.

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[1] The workshop report is available from http://sedac.ciesin.columbia.edu/rs-treaties/.

# ACRONYMS

| | |
|---|---|
| CBD | Convention on Biological Diversity (Rio de Janeiro, 1992) |
| CCD | International Convention to Combat Desertification in those Countries Experiencing Serious Drought and or Desertification (Paris, 1994) |
| CEOS | Committee for Earth Observation Satellites |
| CIESIN | Center for International Earth Science Information Network, Columbia University |
| CMS | Convention on the Conservation of Migratory Species of Wild Animals (Bonn, 1979) |
| COP | Conference of Parties |
| DEM | Digital Elevation Model |
| ESA | European Space Agency |
| GEF | Global Environmental Facility |
| GEO | Group on Earth Observation |
| GEOSS | Global Earth Observation System of Systems |
| GIS | geographic information system |
| IBAMA | Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais |
| IGOS | Integrated Global Observing Strategy |
| ISPRS | International Society for Photogrammetry and Remote Sensing |
| IUCN | The World Conservation Union |
| MA | Millennium Ecosystem Assessment |
| MAB | Man and the Biosphere Program of UNESCO |
| MARPOL | International Convention for the Prevention of Pollution from Ships (London, 1973 ) |
| MEA | multilateral environmental agreement |
| MSS | Landsat Multispectral Scanner imagery |
| NASA | U.S. National Aeronautics and Space Administration |
| PROBIDES | Programa para la Conservación de la Biodiversidad y Desarrollo Sustentable de Los Bañados del Este |
| Ramsar | Ramsar Convention on Wetlands of International Importance (Ramsar, Iran, 1971) |
| RS | remote sensing |
| SBSTTA | Subsidiary Body on Scientific, Technical and Technological Advice of the CBD |
| SEDAC | Socioeconomic Data and Applications Center |
| TBCA | Transboundary Conservation Areas |
| TBNRM | Transboundary Natural Resource Management |
| TBPA | Transboundary Protected Areas |
| TM | Landsat Thematic Mapper imagery |
| UNCED | United Nations Conference on the Environment and Development |
| UNESCO | United Nations Educational and Scientific Organization |

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# I. INTRODUCTION

Biodiversity conservation and ecosystem management are high on the environmental agenda. Concern for the impact of human activities on “nature” helped launch the international environmental movement in the 1960s. This concern for nature and the loss of natural resources spawned a number of international agreements such as the Convention on International Trade in Endangered Species (1968), the Ramsar Convention on Wetlands of International Importance (1972), and more recently the Convention on Biological Diversity and the Convention to Combat Desertification (both established in 1992). It has also spawned a multi-million dollar research enterprise that has grown from early roots in taxonomic fieldwork to include a large array of sub-disciplines such as conservation biology, restoration ecology, and plant and animal genetics. As technology has advanced, so has the tool kit used by conservationists. The convergence of these three trends in environmental agreements, biodiversity research, and advanced technologies has led quite naturally to the application of remote sensing to ecosystem management and, consciously or unconsciously, to the concerns raised and “legitimized” by multilateral environmental agreements (henceforth referred to as treaties).

Within the last decade a new area of ecosystem management has arisen in recognition of the fact that ecosystems do not respect borders. Migrating birds, mammals or plant pollen need no passports or identity papers to traverse national and international frontiers, yet management of natural areas is often fragmented among many jurisdictions, rendering it less effective than it might be. Thus, a new field of transboundary natural resource management (TBNRM), often implemented through transboundary protected areas (TBPAs), seeks to promote cooperation among government, NGOs and civil society working on conservation on different sides of national or international boundaries (Sandwith *et al*. 2001). Given the synoptic view of remote sensing, transboundary conservation is a natural candidate for applications that seek to provide a coherent base maps and conservation assessments across national or international borders.

This report addresses these two strands of remote sensing applications, both of which are united by a concern for biodiversity conservation and ecosystem management in an increasingly connected world of agreements and transboundary environmental concerns. The report begins with a short primer on remote sensing technologies (Chapter II). It then proceeds with a discussion of the monitoring needs for ecosystem management treaties and transboundary conservation areas (Chapter III). The heart of the report is a chapter that provides examples of the wide variety of remote sensing applications that are relevant for ecosystem management treaties and/or transboundary ecosystem management (Chapter IV). The focus of this chapter is on terrestrial ecosystems, including wetlands. Chapter V summarizes lessons learned from these applications, provides a frank assessment of the strengths and limitations of remote sensing as a conservation tool, and points to new developments on the horizon.

Considerable detail on individual treaties and the provisions of those treaties that might lend themselves to remote sensing applications is provided in Annexes 1 and 2. The first annex addresses global treaties and the second annex addresses regional treaties that the author deemed most relevant. Finally, Annex 3 provides a list of remote sensing resources available to the conservation community, and Annex 4 provides a table of satellites and sensors.

# II. REMOTE SENSING PRIMER

*This chapter provides an overview of remote sensing technology for non-specialists. The focus is on satellite remote sensing of land resources using passive instruments. Those with an understanding of the mechanics of remote sensing may wish to skip to Chapter III.*

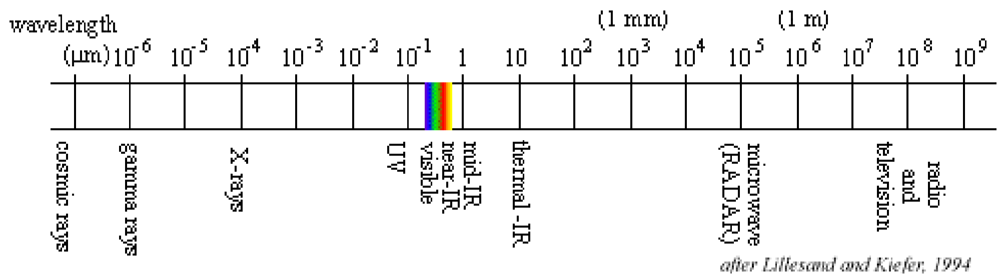
The process of remote sensing involves the detection and measurement of radiation of different wavelengths reflected or emitted from distant objects or materials, by which they may be identified and categorized by class/type, substance, and spatial distribution. Although full training in remote sensing techniques can take several years to acquire, the principles of remote sensing are relatively straightforward and easily understood by the lay person who understands basic physics.

## *II.A. Principles of Remote Sensing and Sensor Characteristics*

Remotely sensed data are collected in many regions of the electromagnetic spectrum (Figure 1). Data recorded from each part of the spectrum can provide distinct information on characteristics of the Earth's surface or properties of the atmosphere. For example, healthy green vegetation reflects highly in the near-infrared region of the spectrum, whereas water bodies tend to reflect only a small amount of incoming radiation in the visible region. All remote sensing instruments collect electromagnetic radiation that is reflected, emitted, or scattered from the Earth's surface and atmosphere. So-called active sensors such as radar and lidar emit energy that bounces off the land or water surface and returns to the sensor to be recorded. The way the energy is directed or scattered by the surface, and the time it takes for the energy to return, reveals information about surface characteristics. Because of the long wave lengths employed by radar, the signals can penetrate clouds, thereby allowing scientists to record information about normally cloud-covered areas. This is an asset in tropical areas such as the Amazon River basin.

Passive sensors, on the other hand, typically rely on solar illumination of the Earth's surface, though some are equipped to detect night-time lights and gas flares. These sensors are "passive" because they do not emit their own energy, but rather rely on energy reflected or emitted from the earth's surface. Unlike radar sensors, they are unable to penetrate clouds. It is interesting to note

**Figure 1. The Electromagnetic Spectrum**




*Source: ICRSE, Remote Sensing Core Curriculum, Volume 2, Lecture 2.2.*

that the visible portion of the spectrum—those wavelengths that humans can see—is a very small segment of the spectrum. Part of the strength of remote sensing is that it enables scientists to "see" portions of the spectrum that are outside the range that the human eye can detect. Scientists can combine non-visible portions with visible ones through color composites, assigning each *band* (or portion of the spectrum detected by the instrument) the colors red, green and blue.

A sensor's bandwidth and the number and placement of bands (within the spectrum) define its *spectral properties*. Panchromatic sensors measure reflected energy in a single portion of the electromagnetic spectrum, usually the visible to near-infrared regions. Multi-spectral sensors, on the other hand, collect reflectance information in discrete portions of the spectrum, with each being recorded as a separate image called a band or channel. When these bands are displayed on a computer, with one band shown through each of the blue, green and red channels of the monitor, they yield a combined color image. Landsat 7's Enhanced Thematic Mapper, for example, is a multi-spectral instrument that collects data in eight bands – three visible (one each for blue, green, and red), a near-infrared, two middle-infrared bands, a thermal-infrared and a higher spatial resolution panchromatic band. By contrast, the Moderate Imaging Spectrometer (MODIS) collects data in 36 different spectral regions, and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is a hyperspectral instrument that collects data in 224 spectral bands. A table of sensors and their capabilities is included in Annex 4.

Ultimately, what a sensor measures is the intensity of radiation that actually reaches the sensor, which is termed the *at-satellite radiance*. Radiance values are commonly translated into digital numbers (DNs). The possible range of DNs varies between sensors, although ranges of 0-255 (for 8 bit images) and 0-1023 (for 10 bit images) are common, with higher values corresponding to greater brightness. Radiance is captured by a two dimensional array of picture elements, or *pixels*. A DN for a pixel in a specific band is determined by the intensity of the radiance captured for that particular portion of the electromagnetic spectrum. If space-based passive sensors were able to accurately, precisely and repeatedly capture the actual reflectance from a feature on the ground, regardless of the time of day, season or weather conditions, much of the hard work of image processing would be eliminated. But the reality is that the atmosphere scatters radiation that is reflected back out to space. Smoke, haze, clouds and humidity exacerbate the problem, and can block reflected energy entirely. Data from shorter wavelengths are more likely to be blocked or scattered by clouds or atmospheric particles, whereas images using sensors capturing longer wavelengths are less likely to be disturbed by atmospheric conditions between the sensor and the target object.

*Spatial resolution* is measured in terms of the size of one pixel projected on the ground. Spatial resolution is directly tied to the size of the features that can be resolved (or "seen") on the ground.

The higher the resolution, the less likely that there will be "mixed pixels" in which radiances effectively represent an average of land cover types in the ground area represented by that pixel (e.g., half lake and half forest). Commercial high resolution sensors have a spatial resolution in the 0.6-10 meter range, medium resolution sensors fall in the 10-50 meter range, and low resolution sensors have greater than 50m resolution.[2] Until the advent of the commercial satellites IKONOS and QuickBird, with resolutions of one square meter or finer, high resolution imagery was the exclusive province of intelligence-gathering agencies. Most conservation oriented applications do not command the financial resources required to obtain such high resolution data, nor are images of this resolution generally required. To date, the most often used data for ecosystem applications are medium resolution data from satellites such as Landsat and SPOT with nominal resolutions of between 10 (panchromatic) and 30 meters (multispectral).

*Repeat cycles* or *revisit frequencies* relate to how frequently a sensor revisits and images the same spot on earth. For satellite-based sensors, it is affected by the altitude of orbit and the angular field of view of the sensor and whether the platform is capable of "looking" to the side as opposed to only straight down (or *nadir*). A sensor with a wide field of view (i.e., with a wide ground track or swath) can image the same place from different angles more frequently than a sensor in the same orbit with a narrower field of view and smaller swath.

The repeat cycle can be important for applications related to biodiversity conservation and ecosystem management. Some satellites have a repeat time in the range of days or weeks, while others have a repeat time of hours. Frequent repeat times can be particularly important for tropical regions where cloud cover can obscure large areas. The more often a satellite covers an area, the more likely that a researcher will have at least one cloud-free image during the period of interest. Using several images of the same place, across a growing season can greatly aid in deriving much more detailed information as to the composition, structure and changes within detailed land cover units.

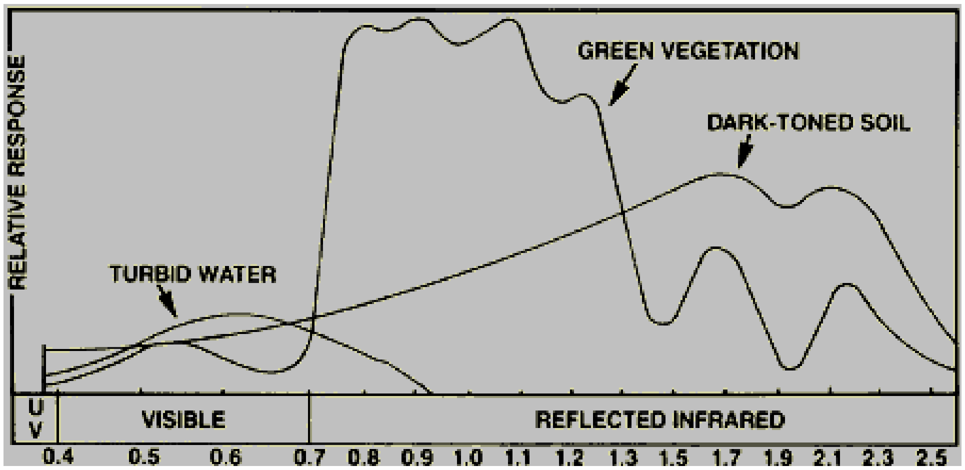
### *II.B. Processing Remote Sensing Imagery*

Much of the technical work of remote sensing involves pre-processing and applying radiometric and geometric corrections to imagery to compensate for errors due to factors such as atmospheric interference of incoming radiation and sensor and data stream irregularities. Once such corrections are applied, imagery must be georeferenced to a particular coordinate space using known ground information or "ground control." The processed data can now either be visually interpreted or classified using manual or automated processes. The main elements of visual image interpretation involve gradients of tone or color, resolution, size and shape, texture and pattern, site and association, and height and shadows. Given their knowledge of the characteristic spectral signatures of different land cover types (Figure 2), scientists my inspect black and white images of each band separately in order to identify features and patterns.

Image classification is the process of creating discrete classes or categories of land cover, utilizing information from some or all of the bands to group together pixels with similar spectral signatures. Supervised classification entails providing the software with sample pixels that represent specific features, such as boreal forest, and then having the computer classify every pixel with a similar *spectral signature* as boreal forest. Analysts may also use images from different seasons in order to discriminate vegetation cover types that have different phenologies,

[2] The definition of what constitutes high to moderate to low resolution sensors has changed over time as the technology has improved.

**Figure 2. Spectral Signatures for Common Surface Types.** *The spectral signature is the characteristic pattern of electromagnetic radiation that is obtained at the sensor from that land cover type across different portions of the spectrum. The numbers across the bottom represent wavelengths in nano-meters.*




*Source: USGS, Earth Shots: Satellite Images of Environmental Change.*

such as deciduous and evergreen forests. In unsupervised classification, the analyst specifies the desired number of classes, and the computer automatically sorts the pixels according to their spectral signatures. The analyst then labels the resulting groups based on some local knowledge of the land cover patterns. Although traditionally analysts have come up with their own land cover classification systems based on the specific end use requirements of a research project or client, there have been recent calls for analysts to use hierarchical, standardized land cover classifications systems to enhance comparability across research projects (Lepers *et al.* 2005). FAO has developed one such system, the Land Cover Classification System, now in its second version (Di Gregorio and Jansen 2000).

Once classified, it is necessary to verify or validate that the output product accurately represents the actual composition, content, structure or land surface characteristics being mapped. Validation requires either field visits, ground-truthing or comparing the classified image with existing maps or images of sufficient detail. Statistics can be derived for the classified imagery indicating the general and specific (class-wise) agreement between the pixels or classes used, letting the user know which were classified correctly and which ones were not.

Validation results are also sometimes presented as a percentage value associated with the map that communicates how accurate the map is on a per pixel basis. Since the highest confidence rankings reported by satellite land cover data sets are between 85% and 90% (for the easiest types of land cover to classify), for an image with a per pixel accuracy of 85% the likelihood that one pixel out of four is incorrectly classified is close to 0.50.

| Per-pixel accuracy | Probability that 4 out of 4 pixels are correctly classified |
|---|---|
| 65% | 0.178 |
| 75% | 0.316 |
| 85% | 0.522 |
| 95% | 0.815 |

Similarly, for any given 3 x 3 grid, the probability that all cells are 100% correctly classified based on certain per-pixel accuracies is as follows:

| Per-pixel accuracy | Probability that 9 out of 9 pixels are correctly classified |
|---|---|
| 65% | 0.02 |
| 75% | 0.075 |
| 85% | 0.23 |
| 95% | 0.63 |

DeFries and Los (1999) point out that the accuracy is most meaningfully judged in the context of the application for which the data are being used. In climate modeling, for example, per pixel accuracies of between 80% and 90% for characteristics like leaf area index (LAI) and surface roughness are largely satisfactory. However, if a map that has only 70-80% per pixel accuracy is used for a local biodiversity conservation application, this means that for any given matrix of pixels there is a high probability that a significant number of them will be incorrectly classified. Such high levels of inaccuracy are largely unacceptable unless the data are utilized only for an indicative sense of where different land covers are located.

The intended application of the land cover classification will also dictate the spectral, spatial, and temporal characteristics of the imagery that the analyst selects. For example, because of costs, data volumes and time processing constraints, high spatial resolution imagery are generally not the most appropriate for global or regional composites. The IGBP Land Cover data set which was the early standard for global land cover data was developed using 1km resolution data from the Advanced Very High Resolution Radiometer (AVHRR). The more recent Global Land Cover 2000 data set was developed using a regional team approach from SPOT's VEGETATION sensor, also a 1km resolution sensor. Only recently has a global composite of ortho-rectified Landsat images been developed, and land cover data derived from this image mosaic are available for much of the world (EarthSat *undated*).

Land-cover change analyses are one of the primary uses of remote sensing data in the field of biodiversity conservation. Change detection requires images of the same area at two points in time. In the ideal scenario, these images would be from the same sensor and from the same season of the year, since the presence or absence of foliage, snow cover, soil moisture, and other factors all affect the spectral signature. However, remote sensing scientists are adept at dealing with data limitations, and can account for differences in sensors and seasonality of imagery using a variety of techniques. The final products of land-cover change analyses include maps delineating areas of change between specific cover types, and change matrices that show the percentage or total area changes between classes for the dates in question. Note, however, that map accuracy problems for either one or both time slices can multiply the error in land cover change products.

Remote sensing imagery is also commonly used to develop maps of greenness or vegetation productivity utilizing a band-ratio technique called the normalized difference vegetation index (NDVI).[3] This can help in understanding seasonal phonological patterns, as well as patterns of drought and rainfall abundance. Each of these techniques – visual interpretation, image classification, land cover change analysis, and calculation of NDVI – have been used in different ways by the authors of the studies described in Chapter IV of this report. But the studies go a step

[3] An index calculated from radiation measured in the visible and near infrared channels from satellite-based remote sensing.

further to apply specific metrics related to ground-cover spectral signatures, fragmentation, and land-cover change to understanding patterns of biodiversity, biodiversity loss and ecosystem functioning on the ground.

# III. MONITORING NEEDS FOR TREATIES & TRANSBOUNDARY CONSERVATION

Before we can ask the question of what can remote sensing do for ecosystem management treaties and transboundary conservation, it is important determine their respective data and information needs, and their provisions for monitoring and assessment.

## *III.A. Data and Information Needs for Treaties*

International environmental policy is typically cast in the form of bilateral or multilateral environmental agreements (MEAs), which are agreements forged between governments to collectively address an environmental problem. Although these agreements (henceforth referred to as treaties) have sometimes been criticized as being ineffective in stemming environmental losses, it must be recognized that environmental treaties largely set the agenda for international conservation efforts and provide the sole context in which to hold States accountable for biodiversity conservation within their national borders. Although imperfect, they are evolving into ever more significant mechanisms for conservation and cooperation.

In recent decades environmental treaties have grown in number, scope, and complexity. A search of the IUCN Environmental Law database turned up 138 treaties related to “wild species and ecosystems” and 300 “environmental” treaties at the global, regional and bilateral levels.[4] Many of these treaties contain provisions for monitoring, reporting, and assessing both environmental and behavioral data. Table 1 provides selected provisions in summary form for the global treaties of greatest relevance to ecosystem management, and Annexes 1 and 2 provide more detailed descriptions of the treaties and those articles most relevant to monitoring. As can be seen from Table 1, there are many rules, standards and monitoring provisions for which remote sensing can and does provide valuable information.

Environmental treaties are agreements between states, but the actors who affect environmental conditions are often businesses and individuals. This means that treaties must mesh with regulatory structures within states, and that data needs for monitoring are often more complex than in the case

[4] A similar search of CIESIN’s ENTRI database turned up 40 treaties that are focused on environmental conservation.

| Table 1. Summary of Relevant Rules and Standards and Provisions for Monitoring of Major Ecosystem Management Treaties[5] | | |
|---|---|---|
| **Name** | **Rules and Standards** | **Monitoring** |
| Convention Concerning the Protection of World Cultural and Natural Heritage (World Heritage Convention) | Each Party shall:<br>• integrate the protection of their heritage into comprehensive planning programs, set up services for the protection of their heritage, develop scientific and technical studies, and take necessary legal, scientific, administrative, and financial steps to protect their heritage. | Monitoring is the responsibility of the Parties concerned and the commitment to provide periodic reports on the state of conservation of the site is consistent with the principles set out in the Convention (see Article 29). Parties may request expert advice from the Secretariat or the IUCN, the advisory body for natural heritage sites. |
| Convention on Biological Diversity (CBD) | Each Party shall:<br>• identify processes and categories of activities which have or are likely to have significant adverse impacts on the conservation and sustainable use of biodiversity;<br>• establish a system of protected areas or areas where special measures need to be taken to conserve biological diversity<br>• establish and maintain programs for scientific and technical education and training in measures for the identification, conservation and sustainable use of biological diversity and its components<br>• promote technical and scientific cooperation with other Parties in implementing the Convention | The Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) is a body of the Conference of the Parties (COP) and is to report regularly to the COP on all aspects of its work. Its functions include: providing assessments of the status of biological diversity; assessments of the types of measures taken in accordance with the provisions of the Convention; and respond to questions that the COP may put to the body. The clearinghouse mechanism for scientific and technical co-operation (CHM) provides a needs-driven, decentralized mechanism for information exchange. In decision VII/30, the COP decided to establish goals and sub- targets for identified focal areas to clarify the 2010 global biodiversity target and promote coherence among the programmes of work of the Convention. The Global Biodiversity Outlook is the reporting mechanism for global 2010 information. There is a.flexible framework for national reporting, but nations are encouraged to refer to subtargets described under the 2010 target. |
| Convention on the Conservation of Migratory Species of Wild Animals (CMS) | Range states are to:<br>• prohibit taking of Appendix 1 (endangered) migratory species.<br>• endeavor to conserve and, where possible, restore the habitats of these species; eliminate, prevent, or minimize impediments to their migration; and prevent, reduce, or control factors endangering them. | Parties to the Convention should inform the COP every three years of measures they are taking to implement the Convention for species listed in the Appendices. |

[5] Objectives and more detailed information on each of these treaties are provided in Annex 1.

*Table 1. (Continued)*

| Name | Rules and Standards | Monitoring |
|---|---|---|
| Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention) | Parties shall:<br>• designate at least one national wetland for inclusion in a List of Wetlands of International Importance.<br>• Promote the conservation of wetlands included in the List. | Reports are required when the ecological character of a listed site is changing or is likely to change so that international consultations may be held on the problem. In 1990, at Montreux, the COP called for the maintenance of a Record of Ramsar sites where changes in ecological character have occurred, are occurring ore are likely to occur (the Montreux Record). |
| Convention to Combat Desertification (CCD) | Affected-country Parties undertake:<br>• to address the underlying causes of desertification and pay special attention to the socioeconomic factors contributing to desertification processes.<br>Developed-Country Parties undertake:<br>• to promote and facilitate access by affected country Parties… to appropriate technology, knowledge, and know-how.<br>Elements of National Action Programs may include provisions for:<br>• Strengthening of capabilities for assessment and monitoring. | The Committee on Science and Technology (CST) provides the CoP with information and advice on scientific and technological matters relating to combating desertification and the effects of drought. At the request of the CoP an ad hoc panel was established to address specific issues related to benchmarks, indicators, and early-warning systems. |
| International Tropical Timber Agreement (ITTA) | Members are required:<br>• to furnish, within a reasonable time, statistics and information on timber, its trade, and the activities aimed at achieving sustainable management of timber-producing forests. | Members are expected to submit data annually on their national production, trade, supply, stocks, consumption and prices of tropical timber for the *Annual Review and Assessment of the World Tropical Timber Situation*. Members are required to supply other statistical data and indicators as requested by the Council. There is no independent verification of data or information, but NGOs may address report issues in the Council. |

*Table 1. (continued)*

| Name | Rules and Standards | Monitoring |
|---|---|---|
| Man and the Biosphere (MAB) Program | MAB is not technically a treaty, but rather a site designation. The MAB Program encourages interdisciplinary research, demonstration and training in natural resource management in countries with MAB sites. MAB contributes thus not only to better understanding of the environment, including global change, but to greater involvement of science and scientists in policy development concerning the wise use of biological diversity. There are guidelines for establishing MAB National Committees (NC). A MAB NC is responsible for the activities making up the national contribution of a country to the international MAB Programme in the field of biodiversity conservation, sustainable development, capacity building and information sharing, and in particular in promoting the biosphere reserve concept and the World Network of Biosphere Reserves. | The International Co-ordinating Council of the Man and the Biosphere (MAB) Program is composed of 34 elected representatives of Member States of UNESCO. The role of the Council is, among others:<br>• to guide and supervise the MAB Program;<br>• to review the progress made in the implementation of the Program;<br>• to recommend research projects to countries and to make proposals on the organization of regional or international cooperation;<br>• to co-ordinate activities with other international scientific programs; and<br>• to consult with international non-governmental organizations on scientific or technical questions. |

*Source: Stokke and Thomnessen 2003 (except for MAB, and with additions for the CBD)* of treaties in those arenas in which governments are the sole actors, such as arms control (Kline and Raustiala 2000). In some instances it may be sufficient to know that a country has passed a law that will address an issue of concern, but in other instances it may be necessary to set up monitoring in order to identify if the treaty is having an impact or the issue of concern is being addressed. This is a potential role for remote sensing.

Most of the global treaties have set up mechanisms for obtaining scientific and technical advice on matters of concern to the treaty. In the case of the Convention on Biological Diversity (CBD), it is the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA), and in the case of the Ramsar Convention on Wetlands it is the Scientific and Technical Review Panel (STRP). Often the Parties will direct these scientific bodies to set up ad hoc committees to undertake specific studies that will aid in treaty implementation. Increasingly, these bodies have set up working groups that have as part of their remit the provision of advice on remote sensing or data derived from remote sensing. Examples include the STRP's Working Group 1 on wetland inventory and assessment and the SBSTTA's ad hoc technical expert group on indicators, which has experts from the remote sensing community. According to Kline and Raustiala:

> Collaborative scientific data-gathering and monitoring networks may create a dynamic that fosters learning and change in preferences toward environmental protection as it also enhances the effectiveness of later MEAs. In some MEAs, the provision of new data about underlying environmental problems has been critical to the success of the regime and to the expansion of the regime to new states, which may have disbelieved early data or considered their own ecosystems to be unaffected.

There are many factors that contribute to treaty effectiveness, as measured both by rates of compliance with treaty provisions and observable changes in the environmental problems the treaty seeks to address. However, one that is of particular relevance for remote sensing is the ability to observe from space on-the-ground environmental changes that may be in violation of treaty provisions, and therefore deter activities that are environmentally damaging. Remote sensing has been utilized in the area of marine oil pollution to identify the ships responsible for spills on the high seas (de Sherbinin and Giri 2001), but equivalent applications in the area of ecosystem management and biodiversity conservation are less likely simply because the provisions of these treaties are predicated on voluntary compliance. The only biodiversity treaty with stricter provisions for enforcement is the Convention on International Trade in Endangered Species (CITES), which can ban trade from states that fail to accurately report data on wildlife trade. Remote sensing capabilities are less likely to play a role in monitoring this treaty, though implanted or attached global positioning system (GPS) devices have been used to track animal movements and could in theory be used to monitor trafficking of endangered species.

Just because many biodiversity treaties cannot apply sanctions to member states for non-compliance does not mean that they are necessarily ineffective. Treaties provide several valuable mechanisms for increasing cooperation on conservation issues of interest to multiple states, or for addressing problems of global goods such as biodiversity in which the benefits of conservation may not be shared equally. These include:

- Promoting research on issues of relevance to the treaty mandate through subsidiary scientific and technical bodies.
- Supporting international assessments such as the Millennium Ecosystem Assessment (MA) that provide valuable scientific information that may prompt states to take the objectives of the treaty more seriously. The impact may not be direct. For example, a report can influence public opinion, and the public may in turn pressure law makers to ratify new

treaties or adopt new protocols. Representatives of all the major ecosystem management conventions sat on the board of the MA.

- Convening COPs and other meetings of the Parties to receive technical advice, debate issues and take decisions.
- Leveraging funding for on-the-ground conservation from bi-lateral and multilateral donors such as the Global Environmental Facility (GEF).
- Influencing the agendas and strategies of major conservation NGOs. For example, IUCN's mission – "to influence, encourage and assist societies throughout the world to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable" – directly borrows from Article 1 of the Convention on Biological Diversity (CBD).

Thus, ecosystem management treaties have considerable leverage over international biodiversity conservation efforts, and provide a useful framework for thinking about the application of remote sensing to biodiversity conservation globally, nationally and locally.

### *III.B. Relationship Between the Remote Sensing and Treaty Communities*

In order to fill perceived data gaps, space agencies such as National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have developed collaborative efforts with the treaty community. For example, NASA provided remote sensing data and and supported research for the Meso-American Biological Corridor, a combination of protected areas and managed landscapes that forms a continuous wildlife migration route from Panama to the Mexican border (de Sherbinin *et al.* 2002a).

NASA is also currently funding a collaborative group consisting of experts from 10 conservation NGOs to work on the Convention on Biological Diversity's 2010 targets. The CBD has identified remote sensing as a critical tool for measuring and monitoring the state of biodiversity. SBSTTA Recommendation X/5 links remote sensing with two global indicators of the 2010 goal in particular: 1) Trends in extent of selected biomes, ecosystems and habitats and 2) Connectivity and fragmentation of ecosystems. The NGO group is based in the United States but most of the organizations have strong international networks and all have operational programs in the field. The group is working closely with the UN's World Conservation Monitoring Center (WCMC) to create a Sourcebook on Remote Sensing to be used by nations, organizations, and educational institutions supporting the CBD. This Sourcebook will address monitoring of different biomes and scale and accuracy issues within the framework of the CBD operational structure. It is planned for release in the early part of 2006 (Steininger *et al.* 2005).

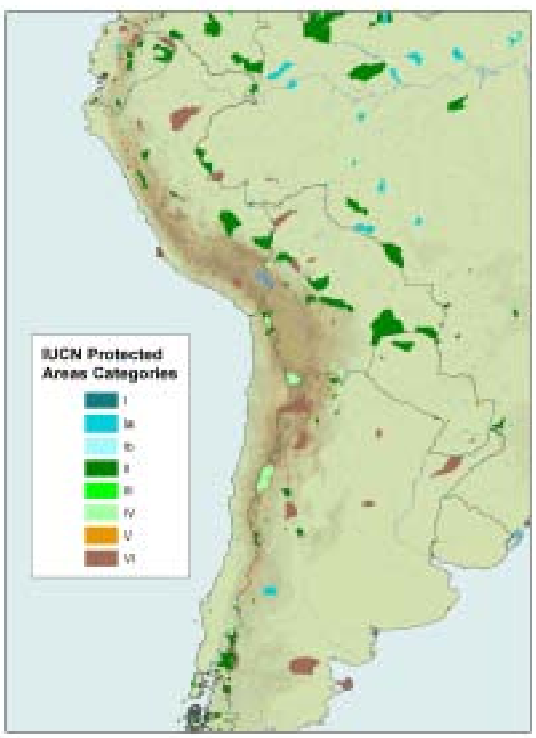
In 2001 the ESA began a project called Treaty Enforcement Services using Earth Observation (TESEO) which focused on the Convention to Combat Desertification (CCD) and the Ramsar Convention as well as the UN Framework Convention on Climate Change (UNFCCC) and International Convention for the Prevention of Pollution from Ships (MARPOL). The project contracted out to consortia of NGOs and remote sensing contractors several feasibility studies on the use of remote sensing in support of the target treaties, and organized several data user brainstorming events that involved representatives of treaty secretariats and UN agencies. TESEO was intended as a catalyst, a way to bring together separate communities that ordinarily do not talk with each other. It established a two-year-long forum in which information gaps were defined along with the remote sensing products needed to address them, and also sponsored some short-term study projects to validate their accuracy (ESA 2003). More recently these activities have been subsumed under the Data User Element (DUE), with a focus on the same treaties.

Finally, since 1999 several workshops have brought members of the treaty and remote sensing communities together. 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 the 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. A two-day workshop was organized by the Socioeconomic Data and Application Center of CIESIN, Columbia University in December, 2000 in Washington D.C. to specifically address remote sensing applications for treaties and featured thematic sessions focusing on biodiversity and ecosystem management, atmospheric change and climate change, and institutional and remote sensing instrument design (CIESIN 2001). The aforementioned TESEO project convened three data user brainstorming events between 2001 and 2003. Lastly, a workshop held under the auspices of the American Institute of Aeronautics and Astronautics (AIAA) in Seville, Spain from 11-15 March 2001 discussed the contribution of space systems to the development and implementation of treaties.

### *III.C. Data and Information Needs for Transboundary Conservation*

Transboundary conservation is a relatively recent interest in the conservation community that has grown out of the reality that many areas of greatest conservation value are in remote areas that frequently abut other countries (see Figure 3). Examples abound, such as around the fringes of the Amazon basin, wilderness areas near Glacier National Park along the US-Canada border, Kruger national park and vicinity on the South Africa/Mozambique border, and the volcanic belt between Congo, Rwanda and Uganda. These areas are increasingly being designated as transboundary parks, and special cooperative mechanisms between states are being set up to ensure their long term conservation.

**Figure 3. South American Protected Areas by IUCN Category.** *Protected Areas are often clustered along border areas, where the human footprint is minimal, leading naturally to the concept of transboundary protected areas.*




IUCN defines a transboundary protected area as "an area of land and/or sea that straddles one or more borders between states, sub-national units such as provinces and regions, autonomous areas and/or areas beyond the limit of national sovereignty or jurisdiction, whose constituent parts are especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed cooperatively through legal or other effective means" (TBPA website).

One approach to transboundary conservation is the Peace Park, initially implemented in southern Africa. Peace Parks "are transboundary protected areas that are formally dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and to the promotion of peace and co-operation" (Sandwith *et al* 2001).

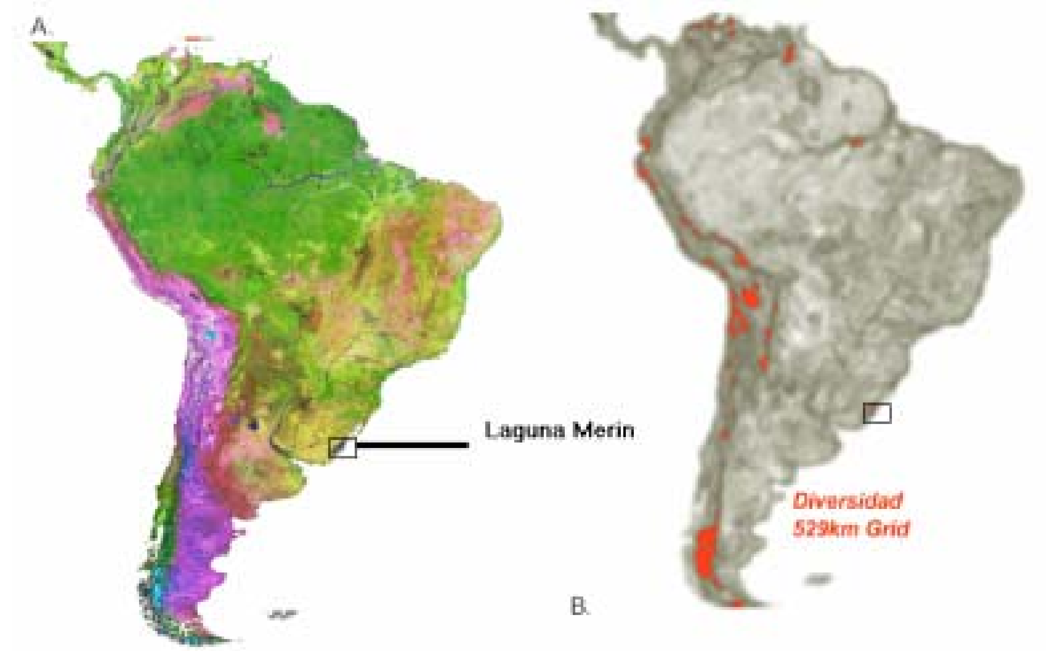
Transboundary conservation requires data and information inputs at different stages. Initially, data on biodiversity richness may be useful to help identify those areas that are of greatest potential value for conservation. This might include a gap analysis – that is, an analysis of land that is of conservation value and an assessment of that portion of the land that is currently protected. At later stages, after a transboundary protected area or management regime is set up, there may well be need for standardized data for both sides of the border area. Given its synoptic view, remote sensing is optimal for such applications.

The subsections below provide case studies on the use of remote sensing in support of transboundary conservation in three different contexts: The wetland complexes surrounding Laguna Merín on the Brazil-Uruguay border, the Upper Paragruay River Basin of central South Ameirca, and Peace Parks of Southern Africa. These illustrate well the utility of remote sensing for conservation planning and ecosystem management.

### *III.C.1. Laguna Merín*[6]

Laguna Merín (Lagoa Mirim in Portuguese) is a large freshwater lake on the border between Brazil and Uruguay. It is the second largest lake in South America after Lake Titicaca in the Andes. The lake and the surrounding wetland complexes play host to a wide array of waterfowl as well as other flora and fauna of international importance. Laguna Merín occupies 3,994 square

**Figure 4. Map Situating Laguna Merín in South America.** *(A) The Global Land Cover 2000 land cover classification for South America. (B) An analysis utilizing the software Diversidad found that Laguna Merín showed up on the continental scale as having high levels of landscape diversity, which translates to high potential biodiversity.*




[6] This case study was conducted under the larger project on Remote Sensing Technologies for Ecosystem Management Treaties, of which this report forms a part.

km, one-third of which is in Uruguayan territory and two-thirds of which is in Brazilian territory (Figure 5). The lake and its surrounding wetlands comprise one of the major transboundary watersheds in South America, supporting a great diversity of flora and fauna, including a large proportion of the region's endemic species and many species of migratory birds. In recognition of its value, the Uruguayan government designated the Bañados del Este on the lake's western shore a Ramsar Wetland of International Importance and a UNESCO Man and Biosphere (MAB), and BirdLife International designated the area just south of the lake as a globally important Endemic Bird Area. On the Brazilian side, the Ecological Station at Taím is covered under the MAB Reserve for the Atlantic Rainforest (Mata Atlantica).While the lake itself remains relatively pristine, the region has seen a dramatic expansion in rice cultivation since the 1970s that has encroached on wildlife habitats, and there has also been an expansion of plantation forests (pine and eucalyptus) and tourism development (on the Uruguayan side). An integrated approach to conservation and development is therefore essential to maintain healthy ecosystems. Fortunately, The basin is under a bi-national treaty for cooperation and resource utilization which foresees "harmonization ... of the studies, plans, programs and projects necessary for achievement of joint works designed to improve utilization of natural resources" (Article 3b), and "the defense and suitable use of mineral, plant and animal resources" (Article 4e) (Parliament of Uruguay 1977).

In the areas surrounding Laguna Merin there is a  floodplain depression system with various wetland ecosystems, including riparian habitats such as gallery forests, temporary marshes, lagoons, swamps, and coastal dunes. There are also some remnants of the original Atlantic Rainforest in the riparian corridors. These habitats support a great variety of flora, for example, the world's largest population of Butiá palms (*Butia capitata*), which are nearly extinct on the Brazilian side. The fauna in the basin is also quite diverse. Migratory birds spend the austral

**Figure 5. Oblique Image of Laguna Merín Viewed from the South.**


*Note: The location of the Brazil-Uruguay border is approximate; it floats about 1 km above the image. This image was captured from NASA's WorldWind data visualization tool.*

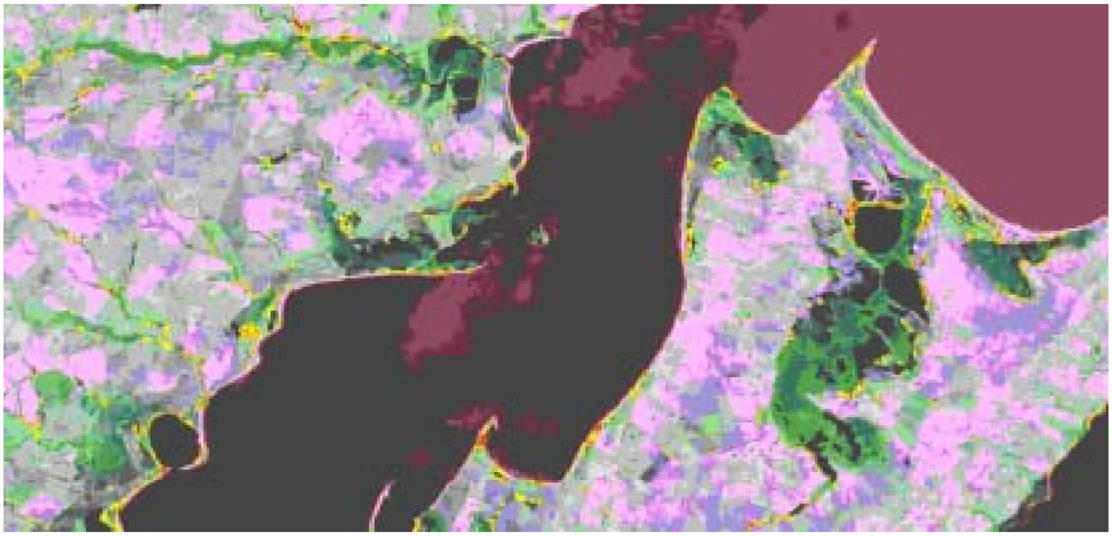
summer in the wetlands and along the lake shore, feeding, mating and resting from their long journey from one hemisphere to the other. Among them are seagulls, sea swallows, plovers and sandpipers. The lake also plays host to a variety of resident and migratory bird species such as coscoroba swans (*Coscoroba coscoroba*), southern screamers (*Chauna torquata*), roseate spoonbills (*Platalea ajaja*), maguari storks (*Ciconia maguari*), swamp cardinals (*Paroaria coronata*), ducks (*Dendrocygna bicolor*, *Amazonetta brasiliensis*, *Netta peposaca*) and, one of the symbols of the region, the black-necked-swan (*Cygnus melanocoryphus*). There are a number of big herbivorous rodents such as the coypus (*Myocastor coypus*) and the capybara (*Hydrochoerus hydrochaeris*), and there are predators such as the caiman (*Caiman latirostris*) and otter (*Pteronura brasiliensis*).

The main goal of the remote sensing pilot project was to construct baselines of ecologically relevant land cover units that reflect their relative importance to migratory water fowl, wading and shore birds and resident passerine and non-passerine arboreal bird species (Figure 6). The process was informed by field work in March and October 2004 on both sides of the lake, conducted by a bi-national team of biologists in the areas in and around Arroio del Rei (Brazilian side) and to the south of the Rio Tacuari (Uruguayan side). Given the importance of hydrological dynamics to the ecological functioning of the wetlands surrounding the lake, land cover units were delineated using eCognition software and multi-temporal Landsat imagery representing different water levels.

The pilot project also sought to test the utility of a software package called Diversidad, which utilizes the diversity of pixels in an the image as a proxy for biodiversity richness (see section IV.1 below). Figure 7 presents a portion of the results of a Diversidad analysis of the entire basin. Further explorations of Diversidad values in conjunction with species lists derived from the field surveys were inconclusive. There was found to be a reasonably high correlation between pixel diversity and bird species richness for the October survey ($R^2$ of .20, P<.10), but correlations between pixel richness and plant diversity were statistically insignificant.

**Figure 6. Land Cover Types of Importance to Birds.** *The remote sensing work and field surveys identified the following land cover types of importance to the area's birdlife: (1) coastal dunes and lake, (2) seasonally flooded wetland (3) wet gallery forest, (4) riparian edge forest, (5) Dry upland forest, (6) seasonally flooded forest, and (7) crop matrix (rice-pasture rotation).*

**Figure 7. Diversidad Image of Central Laguna Merín.** *In this image Diversidad hotspots have been overlaid on to a thematic vegetation map. Yellow corresponds with regions where potential diversity was between 75 and 79 percent, orange regions are where potential diversity was between 80 and 84 percent, and red regions are those with potential diversity values are equal to or greater than 85 percent.*



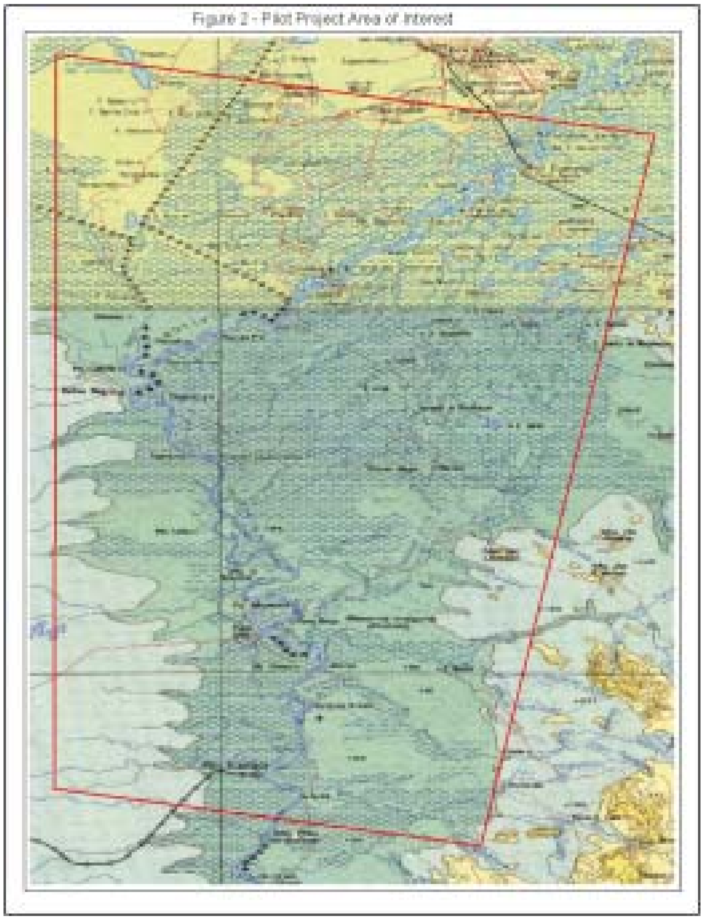
The remote sensing and field work have highlighted the importance of conserving remaining habitats in the basin. By establishing adequately detailed geospatial baselines and conservation priorities, and by providing decision support templates, future surveys and conservation efforts can be optimized to protect and conserve regional resources. The tri-national character of the work – with researchers from Brazil, Uruguay and the United States – has helped to foster collaboration and capacity building among the partners.

### *III.C.2. Upper Paraguay Basin*[7]

The completion of the Pantanal Tri-national Pilot Project in October 2002 was the initial step in the development of a comprehensive GIS and remote sensing database for conservation planning and a data distribution network for the Upper Paraguay River Basin (UPRB). The pilot area covers the Otuquis in Bolivia (all of which is a newly designated Ramsar site), the Nabileque in Brazil (which is soon to be designated a Parque Estadual and a Ramsar site), and the Río Negro in Paraguay (partly included in the Río Negro Ramsar site) (Figure 8). Partners from governmental and non-governmental (NGO) agencies in Bolivia, Brazil, Paraguay and the United States have been collaborating on remote sensing and spatial data development tasks. Remotely sensed data was recognized as a vital application for studying inaccessible or remote areas at a regional scale and for change detection analysis. The data produced by the project are being used to model the effects of past, current and future land-use practices and to determine boundaries of future protected areas or prioritize action for restoration in the UPRB.

[7] Material for this section was derived from a case study written by Montserrat Carbonell and available at http://sedac.ciesin.columbia.edu/ramsardg/casestudies/pantanal.html (last accessed on November 14, 2005)

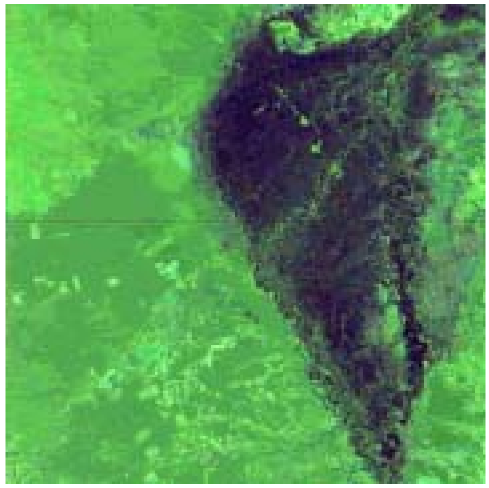
**Figure 8. Upper Paraguay River Basin.**




The Pantanal is one of the world's richest ecosystems. Due to its location in the center of South America, it has fauna and flora typical of the Amazon, Chaco, Cerrado, Dry Chiquitania Forest, and Atlantic Forest ecosystems, which contribute to its high biological diversity. It includes more than 300 species of birds, 190 species of fish, 70 species of amphibians, and 50 species of large mammals (WWF 2002). It is especially important for migratory birds and provides habitat for populations of Giant River Otter, Marsh Deer, Tapir and Jaguar that are at risk in the region and elsewhere in the world (WWF 2002). The Pantanal is the world's largest continuous freshwater wetland, approximately the size of Honduras, Nicaragua and El Salvador combined, with an estimated area of 150,000 km$^2$ of which 110,000 km$^2$ are wetland (Scott and Carbonell 1986). Its boundaries extend across the borders of three countries: Bolivia, Brazil and Paraguay, but more than 70 percent of the Pantanal is located in Brazil (Dolabella 2000). All three countries protect discontinuous areas of Pantanal under different protection regimes such as the National Park Service, State Park Service and Forestry Reserves. Some areas have also been designated as Ramsar sites under the Ramsar Convention. However, much of this region is still unprotected and approximately 95 percent is under private ownership as cattle ranches (Crisman 2000). Primary threats to ecosystem health include road development projects, frequent uncontrolled fires, river channeling, and large-scale agriculture production, all of which can change the hydrology and water quality of the region.

The challenge was to develop common, landscape-level data sets for tri-national natural resource planning. GIS and remote sensing are technologies broadly employed as resource-management tools, and the methods used, data gathered and results obtained through the Pilot Project and ancilliary activities have already been applied to conservation projects by different partners in South America. For example, remote sensing was used to delineate buffer zones and environmental zoning for the management plan for the Taquari State Park in Mato Grosso do Sul, Brazil, to analyze maximum and minimum inundation areas for four sub-basins of the Brazilian UPRB (Figure 9), to delineate wetlands, to study fire incidence, and to classify wetlands in the central Chaco region of Paraguay.

**Figure 9. Area of Maximum Flood Extent, Upper Paraguay River Basin.** *Dark areas represent the floodplain at maximum flood extent.*



### *III.C.3. Peace Parks in Southern Africa*[8]

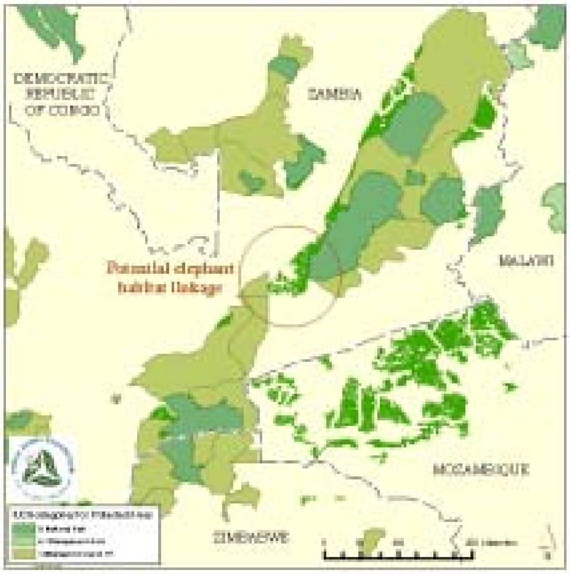
Peace Parks Foundation facilitates the planning and implementation of transboundary conservation areas (TBCAs) primarily in southern Africa. The organization makes use of satellite data in a number of ways, notably to communicate information in a spatially unbiased manner on project goals, progress, monitoring, guidelines for implementation, and visualization. The Foundation has learned that high-quality information plays a vital role in the implementation and management activities of a TBCA. They have used satellite data to map priority natural habitat patches along which elephants could move in their seasonal movement patterns between parks (Figure 10.A). In another instance these patches revealed the state of habitat fragmentation in a study that focused on mapping threats to biodiversity in the regional landscape. In collaboration with other conservation scientists, the Foundation has developed a biodiversity indicator that maps vegetation productivity derived from remote sensing data for natural habitat patches. Vegetation productivity has been found to correlate with biodiversity (Figure 10.B), and is often used as a surrogate to identify patterns of species richness and abundance. The outcomes of this indicator could help to guide TBCA prioritization and planning. In addition, a change in the indicator could signify project progress over time.

Over the years, the Foundation has also made extensive use of satellite data, as true-color images of landscapes, often in a 3D virtual environment during interactive workshops where stakeholders from a wide range of disciplines and backgrounds congregate to discuss the feasibility and priorities of each TBCA. In all the above instances remote sensing data have helped to map the character of landscapes otherwise unknown and/or inaccessible to man. TBCA implementation and management occur on many spatial levels, from the detailed (local scale, TBCA) to the general (regional scale). Within this framework of operation, remote sensing data and information – being available in fine, medium and coarse resolutions on a regular basis – form a integral part of the spatial database at Peace Parks Foundation.

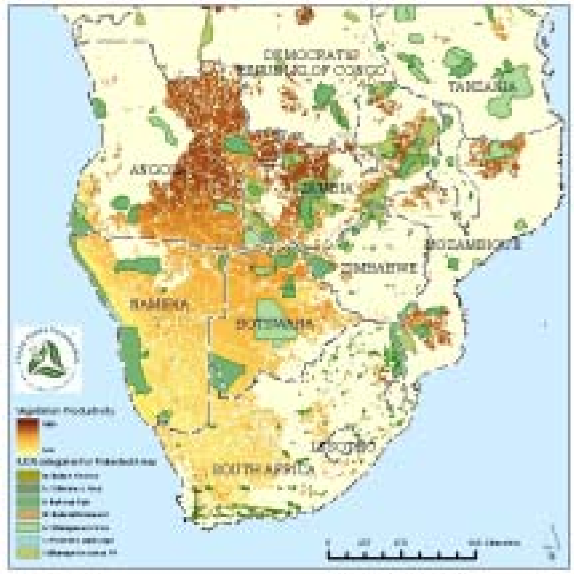
[8] This case study was provided by Nadia van der Merwe, a GIS & Remote Sensing Analyst for the Peace Parks Foundation in South Africa.

**Figure 10. Sample Remote Sensing Applications for Peace Parks.** *(A) Elephant migration corridors - dark green areas represent national parks and light green areas represent management areas. (B) Patterns of species richness and abundance in southern Africa.*

**A.**




**B.**



# IV. REMOTE SENSING FOR BIODIVERSITY CONSERVATION AND ECOSYSTEM MANAGEMENT

Since the advent of terrestrial civilian remote sensing in the early 1970s, much has been written about the ability of remote sensing (RS) technologies to contribute to biodiversity conservation, particularly through the monitoring of tropical deforestation (Tucker *et al.* 1984, Malingreau *et al.* 1989, Stoms and Estes 1993, Turner *et al.* 1995, Sayre *et al.* 2000). The application of geospatial analyses for biodiversity research and conservation has increased dramatically in the past decade, aided by the progressive improvements in the software tools and computing power. Although geographic information system (GIS) approaches have constituted the bulk of such applications, the use of satellite remote sensing for biodiversity conservation and ecosystem management has seen a steady growth as well. This trend will continue for the foreseeable future as the quantity of data increases and the cost of imagery declines. Table 1 provides a list of major applications of remote sensing to ecosystem management and biodiversity conservation.

This chapter begins by examining a range of remote sensing applications in support of biodiversity assessment, beginning with a survey of studies that have examined the relationship between the spectral signature of different land cover types and species richness.[9] The chapter continues with a review of studies that looked at biodiversity characterization at the landscape level, and studies that have looked at the relationship between remote-sensing derived metrics of habitat loss and fragmentation and biodiversity loss. Finally, consideration is given to the application of remotely sensed imagery for parks and protected areas (PAs) management.[10] The research presented here suggests that there is continued promise in the application of remote sensing for biodiversity assessment and conservation, especially as new remote sensing instruments become available, but that the field lacks a set of standard methodologies that could move remote sensing applications from an experimental to an operational stage of implementation.

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[9] Most of the studies were in peer reviewed journals and identified by a key word search on “remote sensing AND biodiversity” through the ISI Web of Knowledge. Emphasis was placed on articles published since 1998. Additional studies were culled from conference papers and online articles.
[10] Annexes 1 and 2 of this report provide additional examples of remote sensing applications with reference to specific treaty provisions.

**Table 2. Ways in which remote sensing imagery can assist in ecosystem management and biodiversity conservation**

1. Providing data for vegetation/land cover mapping to describe broad patterns of distribution of plant communities.
2. Providing data as a complement to field data for mapping and characterizing species habitats.
3. Assisting stratified random sampling strategies for field inventories by ensuring that different habitat types are adequately represented.
4. Identifying biodiversity 'hotspots' at broad spatial scales.
5. Facilitating gap analysis assessing the distribution of suitable habitat and protected areas networks in order to determine the degree to which high biodiversity areas are protected.
6. Providing data for landscape fragmentation metrics such as patch size, edge length, connectivity, perforation, etc., in assessments of biodiversity richness, habitat loss, and population-habitat viability.
7. Providing data for leaf area and normalized difference vegetation indices as measures of biological productivity.
8. Monitoring deforestation trends, pollutant emissions, forest fires, the spread of invasive species, climate change impacts, and other threats to biodiversity conservation.

The focus of this chapter is on terrestrial biodiversity and passive satellite remote sensing instruments (see Chapter II for a brief introduction to remote sensing). Most of the studies reviewed here make use of moderate resolution Landsat Thematic Mapper (TM), SPOT, or Indian Remote Sensing (IRS) satellite data. These instruments have spatial resolutions of between 20-30 meters, repeat cycles of between 16-26 days, and multispectral sensors (4-7 bands in the visible, near infrared, and medium to thermal parts of the electromagnetic spectrum).

### *IV.A. Remote Sensing for Predicting Species Abundance*

There have been a number of studies that have sought to predict species abundance based either solely on remote sensing data or on combinations of remotely sensed, elevation, slope and field data. Such applications respond to a need clearly articulated in the texts and decisions of multiple ecosystem management treaties for biodiversity inventory and assessment, as well as for tools for conservation priority setting. Although there is general recognition that the best possible data on species richness and rareness are obtained from field surveys, full field inventories of the vast tracts of land that have not yet been surveyed would be cost prohibitive. Even if cost were not an issue, full surveys are time consuming, and given the rates of habitat destruction in the tropical ecosystems that possess the richest diversity, conservationists generally agree that more expedient methods need to be tested and applied wherever possible. Thus, biologists and landscape ecologists have explored the relationship between remote sensing derived measures of landscape richness and actual field measures of biodiversity in order to determine the degree to which the relationship can be extrapolated to areas that have not been surveyed. Because climate heavily influences potential vegetation and ecosystem dynamics (Udvardy 1975), the subsections below are organized by bioclimatic zone. Summaries of the methods and findings of the studies that sought to predict species presence/absence or richness using remote sensing are found in Table 3.

#### *IV.A.1. Boreal to Semi-Boreal Climate Zones*

A study in Finland sought to predict total and rare plant species richness in agricultural landscapes in the southwestern part of that country using Landsat TM imagery and a digital elevation model (DEM) (Luoto *et al.* 2002). The modeling effort used known correlations between the remotely sensed/DEM data and species richness and rareness in a 13.25 $km^2$ core study area to extrapolate to the entire study area of 601 $km^2$. The core area was divided into fifty-three 0.25 $km^2$ grid squares that were inventoried. A regression analysis performed on data from the core area found high degrees of correlation between the Shannon diversity index, a commonly used index derived from field-based measures of biodiversity, and various land cover types derived from the TM imagery. Spearman's rank correlation coefficients between the Shannon index and remote sensing derived measures ranged from -0.76 for agricultural land, to 0.56 for "other forest" and 0.9 for deciduous forest (all significant at the 0.001 level). The predictive power increased with the inclusion of terrain data such as altitude, topographical roughness, slope angle, and wetness indices derived from the DEM. This demonstrates the utility and common practice of integrating remotely sensed data with other data in a GIS.

The remote sensing analysis was also helpful for identifying several types of biodiversity 'hotspots'. Hotspots of total flora (grid cells with >200 species) and rare species (grid cells with >4 rare species) were mainly found in river valleys. Hotspots of total flora were found where habitat diversity is high and semi-open agricultural-forest mosaic occurs, and hotspots of rareness occurred in sites where extensive semi-natural grasslands and herb-rich deciduous forests were found on steep slopes. There was a high degree of spatial correspondence between grid cells with high overall richness and rarity.

In a study using a similar methodology and based on survey data from 105 squares of the aforementioned 0.25 $km^2$ grids, Luoto *et al.* (2004) examine the capacity of remote sensing-derived measures to predict bird species richness. They evaluated separately the modeling performance of habitat structure, habitat composition, topographical-moisture variables and all variables for model-building and model-testing. The first two, together with the all-variable model, had the greatest explanatory power.  Deciduous forest cover and habitat diversity explained 51 and 54 percent of the variation in bird species richness, respectively. They conclude that RS imagery is useful in predicting both species numbers and total bird density in the landscape at scales of 10-1,000 $km^2$.

### *IV.A.2. Temperate Climate Zones*

Two studies assessed the utility of satellite remote sensing data as a predictor of species richness in the Greater Yellowstone Ecosystem (GYE) of Wyoming and Montana, USA. Debinski *et al.* (1999) utilized Landsat TM data to determine the relationship between habitat categorizations based on spectral reflectance patterns and plant or animal species distributions. Because RS imagery measures (albeit indirectly) the energy reflected by plants and the ground surface, they expected and found a strong relationship between habitat categorizations based on reflectance patterns and plant species distributions. All plant species with 5% or greater cover, 31% of the butterfly species, and 20% of the bird species exhibited significant differences in distribution among TM-derived meadow types. However, a high proportion of the plant species covered 5% or less of any given meadow area, so they conclude that finding relationships between low-cover species and remotely sensed habitats would probably be more difficult. The animal species were less correlated with habitat type identified through RS. They conclude,  "a species must be either common enough and/or habitat-specific enough to exhibit a significant relationship with one or more remotely sensed habitat types."

Also in the Greater Yellowstone Ecosystem, Saveraid *et al.* (2001) found that SPOT multispectral (MS) imagery assists in estimating potential habitats for bird species in different montane meadows, but that it fails to predict bird species abundance. They suggest that in heterogeneous

**Table 3. Summary of studies that sought to predict species presence/absence or richness using RS data**

| Location (Author) | Species/ Indicator | Summary of Methods | Degree of Prediction |
|---|---|---|---|
| Southwestern Finland (Luoto *et al.* 2002) | Vascular plant species richness | Nine different land cover types were derived from TM imagery; these were then compared with the Shannon Diversity Index values for each type. | r values ranged from –0.76 to 0.9, p=0.0001 |
| Southwestern Finland (Luoto *et al.* 2004) | Bird species richness | Nine different land cover types were derived from TM imagery; there were then compared to bird species counts for 105 separate plots. | $R^2$ of 0.51 and 0.54 between decid- uous forest cover and habitat diversity, respect- ively, and bird species richness |
| Islands in the Gulf of Maine, USA (Podolsky 1995) | Mammal richness | SPOT MS imagery for whole islands; the number of pixels of different colors was used as a surrogate for landscape richness; a complete mammal survey was conducted for each island. | r=0.990, p=0.0001 |
| Cornwall, England (Griffiths *et al.* 2000) | Plant species richness (*Poaceae* taxon) | Landsat TM land cover data on landscape structure and plant species richness were compared for sampled tetrads in two classes – the top ten hotspots of richness and ten midspots. Of four biotopes, the coastal biotope provided the most significant results, presented at right. | $R^2$ of 0.55 and 0.69 between mean patch size and total edge, respectively, and species richness |
| Greater Yellowstone Ecosystem, USA (Debinski *et al.* 1999) | Plant, bird, and butterfly species richness | Three forest types and six meadow types were classified using Landsat TM data. Presence/absence data were collected on birds and butterflies in 35 sites composed of three forest types and six meadow types. Plants were sampled at fine-grained (25 1$m^2$ plots) and coarse-grained scales (20 20$m^2$ plots). | 20-30% of animal taxa and 65-100% of plant species were significantly correlated with RS-derived habitats |
| Yellowstone NP, USA (Jakubauskas and Price 1997) | Forest diversity | Landsat TM data were regressed against species composition in 70 stands using data normalized to units of one hectare per stand. | $R^2$ of 0.31 for overstory & understory composition |
| Joshua Tree National Monument, USA (Podolsky 1995) | Plant species richness | Landsat TM data were analyzed along transects that were subsequently field inventoried for plant species. The number of species and different colored pixels encountered per transect were divided by the length of the transect to control for species-area relationship. | r=0.854, p=0.0001 |
| Great Basin, USA (Seto *et al.* 2004) | Bird and butterfly species richness | NDVI measures derived from a single Landsat TM image were used as a surrogate for vegetation productivity, and were related to field data on birds and butterflies collected using standard inventory methods. | $R^2$ of >.5, p<.01, for bird species richness and $R^2$ of >.23, p<.01, for butterfly species richness at the canyon level. |

**Table 3. Summary of studies that sought to predict species presence/absence or richness using RS data**

| Location (Author) | Species/ Indicator | Summary of Methods | Degree of Prediction |
|---|---|---|---|
| Kalahari Desert, southern Africa (Verlinden and Masogo 1997) | Ungulate presence and density | NDVI derived from AVHRR was used as a surrogate for grass greenness, which in turn was related to field data on presence/absence and densities of various ungulate species | NDVI predicted higher density of hartebeest, $p<0.05$ |
| Cornwall, England (Griffiths *et al.* 2000) | Plant species richness (*Poaceae* taxon) | Landsat TM land cover data on landscape structure and plant species richness were compared for sampled tetrads in two classes – the top ten hotspots of richness and ten midspots. Of four biotopes, the coastal biotope provided the most significant results, presented at right. | $R^2$ of 0.55 and 0.69 between mean patch size and total edge, respectively, and species richness |
| Ferlo, northern Senegal (Nohr and Jorgensen 1997) | Avian species richness | Landsat TM data were used in combination with field survey data for 200 m wide transects. A correlation from a multiple region of annual NDVI and TM-derived landscape indices yielded the modest Coefficient of Determination presented at right. | $R^2$ of 0.363 for multiple regression of NDVI & land-scape indices vs. bird species richness |

landscapes such as those in the GYE moderate resolution imagery such as SPOT MS will fail to predict abundances for fine-scale montane meadow communities. Furthermore, birds select breeding areas based on habitat structure, but RS data do not contain enough information on habitat structure. They recommend combining the RS-derived habitat data with additional landscape metrics and habitat data collected in the field.

A study of 18 islands in the Gulf of Maine examined the relationship between mammal richness and landscape richness (Podolsky 1995). Landscape richness was extracted from SPOT MS data and was defined by the number of different land cover classes (out of a total of 64) found on each island. Data on mammal species for each island were collected independently. Because of the strong species-area relationship, the number of pixels and mammals encountered were divided by the size of each island. A total of 22 mammals were found inhabiting the islands, and abundance patterns ranged from 1 to 17 mammals per island. A very high degree of correlation ($r=0.99$, $p=0.0001$) was found between landscape richness as measured by remote sensing and mammal richness. This study is limited, however, by its relatively small sample size, and made no effort to localize within-island abundance distributions.

In the counties of Kent and Cornwall, UK, Griffiths *et al.* (2000) sought to predict plant diversity from Landsat TM-derived structure metrics (i.e., the number, size and area of biotope patches within the landscape). The effective spatial resolution of their land cover data was between 0.5 and 1 hectare, and land cover was mapped to 25 target classes. In the case of Cornwall, plant species data were compiled from long-term records of amateur biologists, and in Kent the data were digitized from distribution maps in the *Atlas of Kent Flora*. A subset of taxon was utilized (Poaceae, Asterceae, and a composite called 'representative species'), and tetrads (4 $km^2$ grid cells) were grouped into two categories: 'hotspots' containing the highest number of species, and 'midspots' representing moderate species richness. Utilizing difference of means tests for the two samples (hotspots and midspots), they found that only the coastal biotope demonstrated the hypothesized pattern of higher species richness in tetrads with lower levels of fragmentation (as measured by higher mean patch size and length of edge with other biotopes). However, for the other biotopes – grass/shrub heath, pasture/meadow, and deciduous woodland – differences were either not significant, or were significant but not in the anticipated direction. Despite limitations in the data sets utilized, they conclude that it is difficult to provide a valid ecological interpretation for the results, and suggest that "the contribution of landscape pattern to diversity may be relatively weak compared to other factors that influence diversity, including biotope quality… and management history."

### *VI.A.3. Arid and Semi-Arid Climate Zones*

Applications of remote sensing to assess biodiversity in semi-arid and arid zones could be particularly useful for identification of degraded habitats under the UN Convention to Combat Desertification and the Dry and Sub-humid Lands Programme of Work of the Convention on Biological Diversity. Podolsky (1995) examined the relationship between plant species richness and "landscape richness" in Joshua Tree National Monument, which is situated in a desert area of southern California. Landscape richness was extracted from Landsat TM data and was defined by the number of different land cover classes found along each of 16 transects. Field surveys of plant species falling within a two-meter swath along the transect were carried out without knowledge of the patterns derived from the remote sensing analysis. To correct for the species-area relationship, all the data were normalized by transect length. A high degree of correlation was found between transects that were spectrally diverse and those with high numbers of plant species ($r=0.854$, $p=0.0001$), but as in the Gulf of Maine study, the specific location of the most species rich areas within each transect was not assessed.

A study in the U.S. Great Basin, which includes most of Nevada and parts of Utah, Oregon and California, tested the relationship between NDVI derived from a single Landsat TM image and bird and butterfly species richness (Seto *et al.* 2004). NDVI is a measure of vegetation productivity. Its advantage is that, in comparison with standard land cover classification maps, it can be easily and quickly derived from RS imagery, thereby providing much more timely information to land managers. The researchers examined the relationship of three measures of NDVI – mean, maximum and standard deviation over a specific sampling area – with patterns of bird and butterfly species richness at various spatial scales. The strongest relationships were found at coarser resolutions and larger sampling extents, where each of the three NDVI measures explained more than 50% of the variation in bird species richness. The relationship appears to be species-dependent, however, with NDVI measures being able to account for only 20% of the variation in the species richness of butterflies. The authors caution that the methodology applied in the study cannot be universalized because locations, grains, and extents for sampling NDVI were determined *a priori* based on field data on birds and butterflies. However, they do emphasize the potential value of NDVI as a surrogate for classified vegetation maps, which require substantial time and effort to develop.

Another NDVI-based study tested the hypothesis that grass greenness, as measured by AVHRR-based NDVI, was correlated with the presence and population densities of calving ungulates in the Kalahari desert (Verlinden and Masogo 1997 as reported in Nagendra 2001). NDVI was not correlated at all with the presence of eland, gemsbok, hartebeest, springbok, or wildebeest, but for density, hartebeest were found to be present in significantly larger numbers ($p<0.05$) in areas with higher NDVI.

Nohr and Jorgensen (1997) utilized a combination of Landsat TM and AVHRR imagery in an attempt to predict bird species richness in the scrub savanna Ferlo region of northern Senegal. A landscape diversity index was produced from a TM pixel analysis, and yearly biomass production was calculated using integrated NDVI. Bird species richness was derived from 12 transects 200 m wide and 3000 m long. A multiple regression model explained 59-68% of the variation in avian species richness, number of individuals and Simpson diversity index. The following factors in the model were significant: TM-derived landscape diversity indices, latitude, plant biomass, bare ground, herbaceous, and woody vegetation.

### *VI.A.4. Tropical Humid Zones*

As the above studies indicate, predicting biodiversity richness in boreal, temperate, arid or semi-arid ecosystems is fairly challenging, even given their homogeneity and relatively low levels of biodiversity. Tropical humid zones, and especially mountainous tropical forests, represent a level of complexity that is several orders of magnitude greater. Applications in such areas therefore push the limits of feasibility for RS-derived surrogate measures of biodiversity. In India's western Ghats, Nagendra and Gadgil (1999) assessed ecotope types derived from Indian Remote Sensing (IRS) satellite data and angiosperm species distributions (excluding grasses) based on quadrats of 1-100 $m^2$, and found that the ecotopes identified were significantly different from each other in terms of plant species composition. Further east, in Meghalaya, India, Roy and Tomar (2000) estimated biodiversity richness from a combination of IRS, terrain and climate data, but they did not test the validity of their maps against field-surveyed data. Abundant research has been carried out on tropical deforestation patterns (see Section IV.C below). However, given the diversity and threats to tropical forest ecosystems, further research is needed to assess the ability of remote sensing imagery to identify species richness.

*Discussion*

Table 3 provides a summary of the results of the above referenced studies, providing a snapshot on the correlations that scientists have found between products derived from remote sensing and field data on species abundance or rareness. These studies represent a variety of ecosystem types and species. It can be concluded from these studies that measures of plant species richness are more likely to be valid than those for animal species. This is partly due to the fact that remote sensing instruments largely register the spectral response of ground cover (e.g., vegetation) and are unable to identify individual animal species. Owing to their mobility, it is also harder to collect field data on fauna, and presence/absence or abundance metrics may be heavily influenced by seasonality, sampling methodology, and simple luck of the draw.

There is unlikely to be a single, one-size-fits-all solution to the problem of measuring species richness from remotely sensed data. Correlations are quite high in selected studies, but there are significant variations in the relationship between remotely sensed and field-collected indicators. These relationships are dependent on a host of factors such as the spatial and spectral resolution of the imagery, the degree of image processing, the scale of mapping, the bioclimatic zone, the species in question, vegetation structure and history, and the season in which the data are collected. Attempts to map landscape diversity or species richness over extended areas necessarily requires some level of field validation in order to establish the nature and strength of the relationship between the remotely sensed data and field-based measures. Yet the extrapolation from known areas should only be attempted to biophysically similar areas where the same climate, topography, and ecosystem dynamics are known to pertain.

Podolsky (1998) has developed a software tool called Diversidad to map species richness at the landscape level. It is based entirely on landscape heterogeneity as measured by the number of different land cover classes in a moving window. Diversidad calculates two values for each pixel in the image, actual diversity and the theoretical maximum diversity. The mathematical models that Diversidad employs are derived from the work of Shannon and Weaver (1949). Although the tool has shown promise in the early studies cited above as well as in a study of biodiversity richness on the rangelands of Wyoming, it has yet to be rigorously tested across a wide range of ecosystem types. An application of this tool for the Laguna Merin study area yielded inconclusive results (see section III.C.1). Furthermore, depending on the area there is reason to believe that a highly diverse landscape (in terms of variety of ecosystems or land cover classes represented) could just as easily be one that is highly fragmented, or that has multiple human land uses, which would imply even lower species richness than homogenous landscapes. Thus, the biodiversity remote sensing appears to be some ways from developing a tool that simply converts pixel diversity, or any other metric for that matter, to a measure of species richness on the ground.

As a general rule, the broader the scale, the better the ability to predict species richness (Nagendra 2001, Seto *et al.* 2004). For example, Mack *et al.* (1997) found that RS data were sufficient at coarse-scales (such as landscape or ecoregion) for predicting broad patterns of bird species richness, but that they could not supplant field surveys for local-level analyses. Thus, we now turn to RS applications at the landscape level.

### *IV.B. Biodiversity Characterization at Landscape Level*

One of the more promising applications of remote sensing is for the characterization of biodiversity at the landscape and ecoregional scales (defined as scales of tens of square kilometers to hundreds of thousands of square kilometers, respectively). At this scale the interest is not so much to determine the presence, absence, or abundance of specific plant or animal species, but rather to provide broad mapping of biomes and plant communities and general indicators of richness by taxonomic group. In the era before remote sensing, mapping of potential vegetation was done by biogeographers making inferences from climate, land forms and topography complemented by extensive personal knowledge (CIESIN *forthcoming*). Remote sensing assists greatly in identifying actual rather than potential land cover.

An example of mapping at a limited spatial scale is provided by Fuller *et al.* (1998), who created a landscape map for tropical forests and wetlands of Sango Bay, Uganda, using TM imagery and field survey data. From 240 sample sites they validated the TM-derived vegetation map and found an 86% correspondence between field and map data. The species data from the field were used to develop biodiversity ratings based on species richness and rarity, which in turn were related to vegetation cover. The combination was used to generate a biodiversity map for the bay with a minimum mapping unit of 900 $m^2$, which is the resolution of TM imagery. The authors defend the fact that the map undoubtedly has errors by indicating that, historically, conservation planning has often been based on subjective assessments, and that habitat maps and biodiversity data have never been complete.

Roy and Tomar (2000) utilize Indian Remote Sensing (IRS) satellite data together with terrain and climate data to characterize biodiversity at the landscape level in northeastern India. The area, close to the Bangladesh border, is topographically variegated and is very species rich. They modeled landscape biological richness as a function of ecosystem uniqueness, species richness, biodiversity value, terrain complexity and disturbance. Although field surveys were undertaken in order to ground-truth the IRS images, there was no effort to independently corroborate the biological richness index.

Nagendra and Gadgil (1999) test a method of nested biodiversity mapping at different scales utilizing IRS data in the Western Ghats of India. The scales were biosphere ($10^8$ $km^2$), ecoregions

($10^5$-$10^6$ $km^2$ ), ecomosaics ($10^2$-$10^4$ $km^2$), and ecotopes ($10^{-3}$-10 $km^2$). At each scale the entities at that level are differentiated in terms of their composition/configuration involving entities at the next lower scale. They hypothesize that if "ecotopes can be identified in the field on the basis of some emergent biological parameters such as vegetation structure, it is likely that they also would possess a distinctive enough spectral signature to be identifiable" using IRS imagery. Ecotopes could then be combined to identify distinct landscape-level patterns. At the ecoregion scale, the resultant map had 205 patches belonging to 11 ecomosaic types. Supervised classification of land cover types defined at the ecomosaic scale were judged, on the basis of ground truthing, to have a per class accuracy of 70-92% depending on the class. Unsupervised classification, in which the computer assigns classes based on spectral similarities alone, had much lower levels of accuracy of between 30-75%.[11]

Hernandez-Stefanoni and Ponce-Hernandez (2004) utilized Landsat TM imagery and field surveys to map the spatial distribution of plant diversity indices on the Yucatan peninsula of Mexico. They found that identification of vegetation classes in the field and derived from remote sensing data were able to discriminate significantly different species compositions in such a way that RS data can provide a useful mechanism for interpolating and scaling up values of diversity indices over the entire landscape. However, they caution that much depends on the degree to which sample sites represent different classes and the incorporation of beta diversity (or between-ecosystem comparisons of species richness) as a component of plant diversity. To ensure proper representation, they suggest the use of species accumulation curves as described in Soberon and Llorente (1993).

Rapid ecological assessment (REA) seeks to exploit the ability of remote sensing to identify vegetation types at the landscape level for rapid identification of areas of particular conservation value. According to Sayre *et al.* (2000), "Every REA is fundamentally based on interpretation of vegetation types from imagery (either aerial photography or satellite imagery), which are subsequently mapped, field verified, and studied for community- and species-level biodiversity." Unlike other biodiversity assessment methodologies, REAs begin with the remotely sensed imagery, and utilize it for delineation of vegetation types and further field study. RS-derived vegetation types can also be utilized as a sampling frame for stratified random sampling of field locations for field inventories.

*Discussion*

RS-derived biodiversity characterization at broad spatial scales can assist in the identification of priority areas for conservation and the targeting of resources for conservation. Such characterization has assisted greatly in gap analysis, in which existing protected area networks are assessed relative to the spatial location of biodiversity (Edwards *et al.* 1993, Armenteras *et al.* 2003), with a view of extending protected status or creating corridors for wildlife migration. RS-derived measures of vegetation types and biodiversity richness can go considerably beyond the 'expert knowledge' usually employed in rapid biodiversity assessments in terms of providing geographic specificity and understanding of habitat intactness for conservation efforts. RS-derived vegetation maps can also provide the sampling frame for the location of field sampling points to assess classification accuracy or to carry out detailed field inventories (Edwards *et al.* 1998). There is a risk of circularity, however, if remote sensing is utilized *ex ante* to identify the location of so-called "biodiversity hotspots," and then field inventories are carried out solely in those locations. Therefore, in order to ensure that biodiversity rich areas or pockets that may

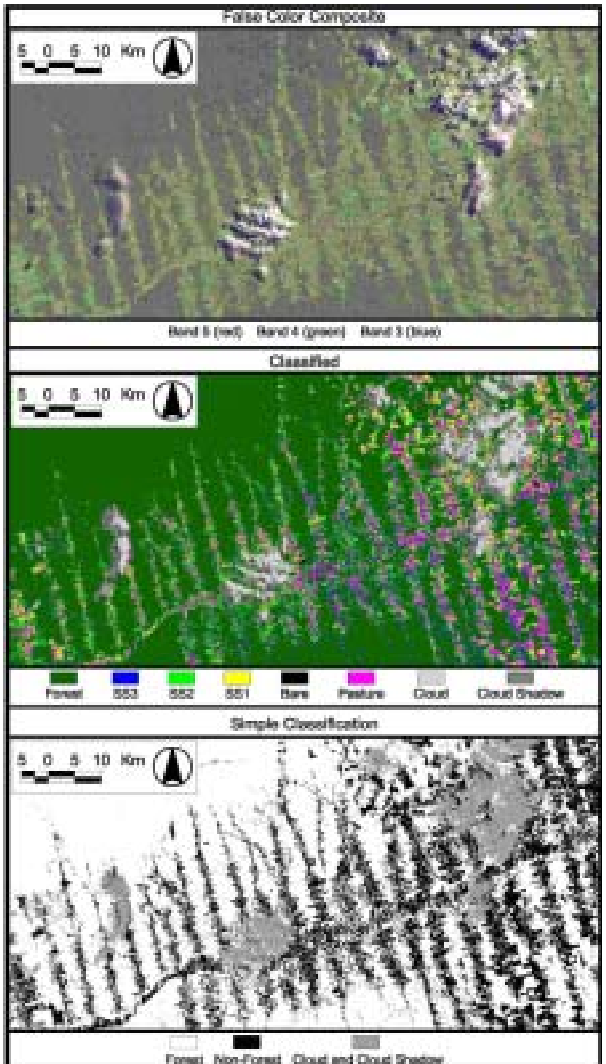
[11] Accuracy assessment of land cover products is vital in the field of remote sensing. Section II.B. contains a brief explanation of accuracy assessment.

contain rare species are not overlooked, it is wise to include several locations outside the anticipated hotspots for evaluation of species richness and rarity.

Foody (2003) suggests that "neural network techniques may be used to provide accurate estimates of species diversity and species composition to more fully describe biodiversity than conventional approaches." These techniques are described more fully in Foody and Cutler (2003).

### *IV.C. Land-Cover Change and Habitat Fragmentation/Loss*

**Figure 11. Image Classification of the "Fishbone" Deforestation Pattern in the Brazilian Amazon.**




*Source: Anthropological Center for Training and Research on Global Environmental Change (ACT), Indiana University, in de Sherbinin* et al. *(2002a).*

Land-cover change maps identify areas that may be under threat from future changes owing to their proximity to past changes. Absent more detailed on-the-ground evidence, they may also be helpful in explaining the mechanisms behind such changes. Land-cover change analyses were pioneered in tropical forest areas such as the Amazon (e.g., Tucker *et al.* 1984, Skole and Tucker 1993), where patterns of forest fragmentation are relatively easy to pick out due to the stark contrast in spectral response between native vegetation and cleared land (Figure 11).

It is generally accepted that habitat loss and fragmentation are the most important causes of biodiversity loss (Foin *et al.* 1998, Armenteras *et al*. 2003). According to Innes and Koch (1998), the degree of habitat fragmentation can play a decisive role in affecting the viabilities of both plant and animal populations in the remaining fragments, and it also appears to influence important ecosystem processes such as habitat resource partitioning, and functional processes such as pollination and decomposition. Thus, there is an important relationship between fragmentation and the decline of selected species, though this relationship varies considerably by species and ecosystem.

In pioneer study that linked habitat loss and fragmentation to species decline, Liu *et al.* (2001) used a combination of Corona and Landsat TM data to map deforestation in a broad area including the Wolong Nature Reserve in China, established to protect the giant panda. The study created RS-derived panda habitat types ranging from highly suitable to unsuitable, which were categorized in part based on landscape metrics derived from the FRAGSTATS software package. From 1965 to 1997 the amount of highly suitable habitat in and around the reserve decreased from approximately 14,000 to under 12,000 ha and suitable/marginally suitable decreased from 74,250 to 59,500 ha, whereas the amount of unsuitable habitat increased from approximately 118,000 hectares to more than 135,000 ha. During the period from 1974 to 1986, the number of wild pandas in the reserve was reported to have declined from 145 to 72. Paradoxically the authors find that declines in the amount of suitable/highly suitable habitat, number of patches, and mean patch size all accelerated significantly after the establishment of the Wolong Nature Reserve in 1975. While innovative in its use of declassified RS imagery from the 1960s, the study is somewhat undermined by the lack of a more reliable and more recent estimates of the panda population.

Kerr and Deguise (2004) undertook a similar study, examining how habitat loss explains the variation in numbers of endangered species in Canada. The authors developed a binary map of natural versus modified habitats using a SPOT Vegetation mosaic for all of Canada. They then examined the proportion of each of 243 terrestrial species' habitats that fall in modified areas. For Canada's 15 ecozones, the number of species at risk of extinction increased with the extent of human modified area ($R^2$ of 0.78, $P < 0.0001$). They conclude that almost all of the habitat loss is due to agriculture, and secondarily to urban land uses.

Landsat TM-derived data on Andean forest fragmentation were utilized by Armenteras *et al.* (2003) in a gap analysis in the eastern Andes of Colombia. Their assessment utilized ecosystems as an indicator of terrestrial biodiversity. Highland ecosystems were found to be the best represented in protected areas due to the preponderance of highland parks in the eastern Andes. The study found that Andean, sub Andean and dry forests were highly fragmented. The authors recommend increasing efforts to conserve dry and oak forests, followed by Andean and sub Andean montane forests near the border with Ecuador. They suggest that analyzing multitemporal imagery will further help refine identification of priority areas for conservation, by identifying those areas under greatest threat of conversion.

In an overview of two major tropical deforestation monitoring efforts, FAO's Forest Resources Assessment (FRA) and TREES II, Mayaux *et al.* (2005) indicate that the annual rates of deforestation identified in the studies were remarkably close – 0.51 and 0.43 percent for FRA and TREES respectively. They note that secondary forests are much more difficult to identify and distinguish from primary forests, even though it can be assumed that some of the original ecological functioning has been altered in the success from forest to cleared land to secondary growth. The methods employed for these assessments is a stratified random sample of 10 and 6% (FRA and TREES respectively) of the total tropical forested area using 20-30 m resolution satellite data.

Most studies of fragmentation versus intactness have focused on forest ecosystems. By contrast, Allnutt *et al.* (2002) examine the effectiveness of TM imagery for a rapid assessment of a xeric habitat of scrub-brush in Chihuahua, Mexico. They found that the imagery was inadequate for identifying habitat intactness; the imagery did indeed successfully identify areas of intact habitat, but areas of severely degraded habitat were also misidentified as intact. They suggest that due to low crown cover, small size and number of leaves, and the low moisture content of the vegetation, vegetative cover makes a low contribution to the overall reflectance of a given pixel. Other factors, such as soil features, litter, and shadow become significant components of the radiative response. Overall, variance in reflection were more often attributable to soil and geological features than to vegetation and habitat characteristics. They conclude that the value of TM imagery is currently limited as a rapid and cost-effective assessment tool for identifying larger blocks of relatively intact desert habitat at the ecoregion scale.

*Discussion*

Innes and Koch (1998) provide a complete list of metrics that can be calculated from remotely sensed imagery utilizing the FRAGSTATS program. The table provides more than 40 measures, grouped into seven broad categories including areas metrics, patch density, patch size and variability indices, edge indices, shape indices, nearest neighbor indices, diversity indices, and contagion and dispersion indices. Griffiths *et al.* (2000) express concern that the ability to compute indices may have outpaced the ability of ecologists to provide valid explanations for their relationships to biodiversity richness or ecosystem processes. Indeed, Innes and Koch write, “There is a major need to ensure that such indices do not become an end in themselves; the objective of such indices must always be as a surrogate for detailed assessments of other biodiversity components (e.g. species diversity, genetic diversity) within forests.” While RS-derived metrics are important for assessing structural diversity, there may be limits in the ability to infer species and genetic diversity from fragmentation measures.

Other research has pointed out the dependence of fragmentation metrics on the spatial resolution of the imagery from which they are calculated (Millington *et al.* 2003). Average patch size and edge length tend to increase with increasing pixel size. As long as metrics are calculated on the basis of moderate resolution imagery, this is not necessarily a problem. But for areas of rapid land-cover change with frequent cloud cover, which includes many areas in the humid tropics, the repeat-time of moderate resolution sensors may be insufficient to capture processes as they unfold. In these cases researchers may need to use AVHRR and MODIS imagery (with their daily global coverage but low spatial resolution), imagery from active sensors (e.g. radar), or airborne imagery flown under clouds. An interesting recent development is low-cost remote-controlled drones, which may be flown at altitudes of up to 4,500 meters with GPS enabled digital cameras and even hyperspectral instruments (Thamm *undated*).

Even in tropical forests, where fragmentation studies are well developed, Nepstad *et al.* (1999) point out that RS images can miss important forest impoverishment problems like selective logging or small scale burning. Landsat TM images capture forest openings created by logging and surface fires, but they are covered over with regrowth within 1-5 years and are easily misclassified in the absence of accompanying field data. Although these processes seldom kill all trees, they damage forests and can impair ecosystem functioning. Thus, as in other areas, complementing RS data with field-based reconnaissance is vital.

Finally, Foody (2003) lists a number of advanced techniques, including pixel unmixing and soft image analysis procedures, for increasing the accuracy of forest area estimation. The author indicates that these methods may also assist in change detection analyses, since they may uncover subtle land cover modifications (e.g. of the type described in Nepstad *et al.*) that conventional post-classification comparison methods can miss.

### *IV.D. Protected Areas and Wildlife Management*[12]

We have already seen how remotely sensed imagery can be utilized in the context of gap analysis to identify areas in need of protection, or to ensure that wildlife migration corridors are preserved between protected areas. Perhaps the most straightforward application of remote sensing is for the generation of land-cover maps within and outside protected areas boundaries (De Maeyer *et al.* 2002). Remote sensing has also been utilized to identify deforestation zones within protected areas, and to assess areas that cannot be accessed due to war or inaccessibility, such as gorilla habitat during the protracted conflicts in eastern Zaire and northwestern Rwanda in the mid-1990s. However, there are a number of other potentially useful applications in the context of protected areas and wildlife management.

DeFries *et al.* (2005) utilize remote sensing to assess the degree to which protected areas in the tropics have become isolated from surrounding ecosystems through loss of habitat in their “buffer zones” (defined as the area within 50 km of the park boundary). Of the 198 IUCN Class I and II protected areas examined (representing the highest degrees of protection), 70% had lost forest habitat in the buffer zones in the past 20 years, and 25% had lost habitat within their boundaries. South and Southeast Asian countries experienced the highest degrees of loss both because of the limited extent of surrounding habitat in the baseline period (1980) and the high subsequent loss. Dry forests in Latin America and Madagascar were also extensively impacted. They conclude, based on analyses of the species-area relationship, that despite limited losses of habitat within park boundaries, the loss of buffer zone habitat has reduced protected areas’ capacity to conserve species richness.

Ganzin and Mulama (2002) evaluate forage resources in Nakuru National Park, Kenya, utilizing NDVI calculated from AVHRR and SPOT VEGETATION sensors. Given the high densities of herbivores in Nakuru, available forage is an important parameter for decision making. The NDVI measures are utilized to calculate carrying capacity and utilization rates. The authors discuss the reality, however, that management options may be few even in the event that the carrying capacity is grossly exceeded. Adjusting the animal load to the capacity of the land may require culling or translocation, neither of which are realistic options in the Kenyan context.

Rabeil *et al.* (2002) utilize SPOT imagery to map habitat suitability in W National Park of Niger, as well as to locate sites for developments like new waterholes, tracks and survey stations. They conclude that in sudano-sahelian environments such as at the W National Park, remote sensing can help to facilitate management decisions and allocation of scarce resources for establishment of survey stations.

Ruiz Moreno *et al.* (2002) utilize remote-sensing derived habitat quality indices (HQIs) as inputs to mathematical population models that run within the framework of cellular automata. The models permit the prediction of the impact of environmental changes on the dynamics of the population under study as well as on the landscape. The habitat distribution obtained from satellite images were utilized to simulate species dynamics with a real landscape structure – the Esteros del Ibera wetlands of Argentina. They propose that this could become a valuable tool for species management where landscape structure and geometry are fundamental.

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[12] Section III.C provides additional examples of remote sensing applications for transboundary conservation areas.

*Discussion*

This has been a cursory examination of the literature on applications relevant to protected areas. It is clear that there is promise for remote sensing applications in protected areas management decision making, but that park managers are often politically or financially constrained in the management actions they can actually implement. In the author’s own experience, working with IUCN field staff to develop GIS capacity, there was often a lack of specialized knowledge of GIS and remote sensing in the field. Staff are also frequently over-extended, such that even the existence of a highly promising management tool does not necessarily ensure its utilization. Partly to address this knowledge gap, NASA’s Jet Propulsion Laboratory has developed a tool called the Protected Area Archive, which makes satellite images easily available by bundling image collections of areas of interest (often, but not always, Protected Areas) with simple and intuitive tools to utilize the data. No knowledge of remote sensing or image processing is assumed (NASA-JPL *undated*).

### *IV.E. Discussion and Conclusions*

This chapter began by examining the relationship between electromagnetic radiation detected by remote sensing instruments and biodiversity abundance on the ground. This review suggests that, in certain contexts, and for certain species, a predictable relationship does exist, and that in these contexts surrogate measures of biodiversity abundance are possible. However, depending on the season, weather, rainfall, atmospheric conditions, and a number of other factors, the spectral values for a given location can vary greatly from image to image (Nagendra 2001). Thus, it is almost certain that the same studies, utilizing identical methodologies but imagery from different dates, would come up with slightly different findings. This means that the models utilized to extrapolate these relationships would need to be calculated afresh with every new set of imagery – a time consuming process. Given the sensitivity of analyses to the date of acquisition of imagery, “turn key” or operational solutions for biodiversity mapping in real time are still some distance in the future.

Nagendra (2001) and Debinski *et al.* (2001) concluded that the use of remotely sensed habitat maps to derive species distribution was capable of wider application, especially for plant species. The research suggests, however, that remote sensing holds only moderate promise for mapping of mobile taxa like birds and butterflies. Only one of the studies reviewed here examined the spectral response of habitats in relationship to the distribution of larger vertebrates, but its results were limited to a peculiar habitat – the islands off the coast of Maine (Podolsky 1995). Liu *et al*. did not use spectral response but changing landscape metrics in relation to the decline in panda numbers.

Turner *et al.* (2001) emphasize the critical importance of being able to bridge the scale gap and link local processes and patterns to processes at broader scales. Remote sensing is part of a suite of tools that can begin to bridge these gaps, and the section of this paper on biodiversity characterization at landscape and regional level covered what is probably one of the most promising applications for remote sensing. Remote sensing can begin to fill in some of the spatial gaps between highly detailed (but necessarily localized) biodiversity inventories with coarser ‘surrogates’. However, such surrogates may only be properly modeled when RS data are combined with other data on terrain, slope, latitude, and climatic data in a GIS.

Accuracy assessment is another concern. Any efforts to extrapolate biodiversity map coverage using remote sensing will necessarily involve some level of mapping error. To be useful for policy making, mapping accuracy needs to be assessed. Edwards *et al.* (1998) describe a methodology developed to assess the accuracy of a landcover map covering 21 million hectares that was prepared for the Utah Gap Analysis. Utilizing stratified random sampling based on ecoregion types identified on the map itself, and adjusting the strategy where it was practically difficult to ground truth a given site (owing to terrain or private land ownership), they found that overall map accuracy was 83%, and that within ecoregion accuracy ranged from 79-85%. As reported above, Nagendra and Gadgil (1999) found similar levels of accuracy in their biodiversity maps of the western Ghats. Seventy percent or higher is likely to be sufficient for most decision-making purposes, but lower levels are likely to be less tolerated, especially if maps of known areas do not conform to expectations.

The research presented here suggests that there is continued promise in the application of remote sensing for biodiversity assessment and conservation, especially as new remote sensing instruments become available, but that the field lacks a set of standard methodologies that could move remote sensing applications from an experimental to an operational stage of implementation. The field is characterized by numerous localized case studies employing many different methodologies. Unlike routine measures of plant productivity such as NDVI, at the present time there does not appear to be any convergence around particular sets of methodologies for assessing biodiversity abundance using remote sensing. While the rapidity of the technological evolution of sensors to some degree mitigates against the development of standardized methods (because sensor specifications change), some standardized approaches are beginning to be developed for moderate-resolution optical instruments such as Landsat TM, SPOT and IRS.

The mainstay of remote sensing for biodiversity conservation has been, and likely will continue to be, land cover maps for conservation planning and management. This is the wellspring from which almost all other applications derive, and has become a permanent part of the arsenal of tools available to conservation professionals.

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# V. CONCLUSION

This report has documented some recent efforts to explicitly apply remote sensing to treaty and transboundary conservation needs, and to promote dialogue between the user community and remote sensing experts. It has also examined a variety of remote sensing applications relevant to the needs of ecosystem management treaties and transboundary conservation efforts. If recent trends are any indication, there is likely to be a steady growth in the number and type of remote sensing applications of relevance to ecosystem management treaties.

Although the promise of remote sensing is great – and to some extent has already been realized – there are still barriers to overcome. Table 4 provides a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis of the current situation of remote sensing vis-à-vis ecosystem management treaties and transboundary conservation. A number of the items listed in the weaknesses and threats columns – such as the high costs of data, the large time investments required, and the need for greater remote sensing capacity in developing countries – are already well known. Section V.A addresses a number of other barriers and constraints, and Section V.B addresses the strengths and opportunities.

## *V.A. Barriers and Constraints*

The words of Paul Uhlir (1995) are prescient, written as they were before the current boom treaty-relevant RS applications:

> "Remote sensing technology and the information derived from it cannot be considered as a technological panacea… Space-based remote sensing therefore must be viewed as an important resource and potential contributor to the overall process of conserving and rationally managing our planetary home. The significance of remote sensing will vary according to each specific area of application and must be analyzed in that individual context."

Among the major issues Uhlir underscores is the difficulty of using remote sensing in a legal context because of issues of data reliability and accuracy. He writes, "The accuracy of the data derived from space may be compromised in either the information-gathering or in the subsequent processing phase." Given that the raw data received by ground stations cannot be utilized until they have undergone radiometric and geometric corrections then further processing to develop derivative products, errors can be introduced at each stage, intentionally or not. This renders them easy to discredit in formal legal proceedings (see Section 5.4 of de Sherbinin *et al.* 2002b). However, because most ecosystem management treaties rely on voluntary compliance this may not be so much of a problem, though it can represent a significant concern if the data somehow lead to faulty decision-making due to a lack of validation.

Participants at a United Nations meeting in 1999 on synergies among environmental treaties called for harmonization of methodologies for data gathering and analysis, and they identified remote sensing technology as "an underutilized resource that should be focused more explicitly on [treaty] monitoring and implementation" (UN University 1999). Unfortunately, the reality is that reporting requirements continue to proliferate, but there is rarely any effort to try to harmonize them. Absent a greater harmonization of requirements, countries find that the results of analyses that are useful for one convention rarely contribute to the information requirements of another.

Another issue is data continuity. Uhlir points out that data archives from early Landsat missions back to 1972 are now largely unusable. Such data represent an important asset for historical analyses. Even more significant, however, is the issue of long-term continuity for operational satellites such as Landsat or SPOT. NASA and ESA are fundamentally committed to cutting-edge scientific research, not to operational land-based sensor programs that are carried out consistently over decades (like those in the meteorological realm). The fragility of the current system was underscored when the Landsat 7 Scan Line Corrector (SLC), which compensates for the forward motion of the satellite, failed on 14 July 2004. Although corrections have been applied, these data cannot be utilized with the same confidence as they were prior to the SLC failure, and a Landsat continuity mission is still several years in the making. According to the US Geological Survey:

> "While every effort will be made to maximize operational longevity for both of the current Landsat sensors [5 and 7], there may be a gap in Landsat data acquisitions. Worldwide, there is no on-orbit or planned system that duplicates Landsat data or collects and archives global land data sets; however, the USGS and NASA are chairing a multi-organizational team that is exploring a number of options for acquiring Landsat-like data during such a gap."[13]

Finally, there is a need for a coordinating institution that could serve as a go-between for the treaty and the remote sensing communities on the issue of biodiversity conservation applications. Although at present there is no organization that is filling this role, there are a number of promising candidates, including the Committee for Earth Observation Satellites (CEOS), the Integrated Global Observing Strategy (IGOS), or the Group on Earth Observation (GEO).[14] IGOS has set up a Carbon Theme with links to the Kyoto Protocol, so it is conceivable that something similar might be set up for biodiversity-related agreements. Kuriyama (2005) suggests that the recently formed GEO, with its planned Global Earth Observation System of Systems (GEOSS), might provide the necessary institutional and data framework for environmental agreements. GEOSS architecture will incorporate sensors and data processing, archiving, exchange and dissemination, under principles of open exchange and assured availability. He recommends that convention secretariats become involved in helping to develop the requirements for the system, with an eye towards using GEOSS to support effective treaty implementation.

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[13] http://ldcm.usgs.gov/ (accessed on November 11, 2005)

[14] Unfortunately, an effort to set up a specialty group on treaty applications under the International Society for Photogrammetry and Remote Sensing (ISPRS) died on the vine due to lack of interest.

**Table 4. SWOT Analysis for Remote Sensing (RS), Treaties and Transboundary Conservation**

| Strengths | Weaknesses |
|---|---|
| • imagery can quickly communicate environmental problems<br>• synoptic view in which national borders are irrelevant<br>• wider range of data becoming available thus expanding the range of potential applications<br>• lower cost data increasingly available<br>• freeware packages available for use by developing countries or small NGOs (see Annex 3)<br>• new sensors launched by developing countries such as Brazil, China, and South Korea<br>• free low resolution data with daily global coverage (e.g. AVHRR and MODIS) for regular monitoring<br>• large scientific enterprise working on applications relevant to conventions from global to local scales | • high costs of data<br>• data gaps – availability of the right data at the right time<br>• technical knowledge required<br>• time investment required for image processing and ground truthing<br>• cloud cover – particularly in the humid tropics<br>• inadequate linkages between the RS research community and the information systems developed by the conventions<br>• inadequate access to RS data in developing countries<br>• weak capacity to analyze data in developing countries<br>• poor product validation and ancillary (e.g., socioeconomic) data availability<br>• most applications are still experimental, and costs of scaling up are significant. |
| **Opportunities** | **Threats** |
| • convention inputs to future satellite missions planning<br>• technical requirements overlaps for diverse treaties<br>• growing interaction between RS experts and treaty community, including direct participation by RS experts in convention technical meetings<br>• conventions may increase the awareness of GEF and other environmental donors of the utility of RS<br>• use of radar data in conjunction with optical remote sensing data provides complementary information (radar data provides information in areas affected by persistent cloud cover)<br>• emergence of the private sector as data providers (e.g., IKONOS & QuickBird) and image processors | • tension between sovereignty of Parties and compliance verification<br>• differentiated reporting requirements among conventions means the same products cannot be used<br>• data accuracy and validation<br>• data continuity – need for archives, operational missions<br>• data acquisition planning – a proper application-oriented management of programmable sensors is necessary to guarantee the right acquisition at the right time<br>• current lack of an international institution to coordinate among space agencies, value-added companies, and treaties for technology and applications development |

*Sources: de Sherbinin and Giri 2001, European Space Agency's TESEO Third User Brainstorming Event Workshop Conclusions, 23 January 2003 (ESA 2003).*

Mayaux *et al*. (2005) state that tropical deforestation monitoring has been hindered by "the inability of the agencies concerned to establish a commonly accepted, independent, cost-effective and long-term mechanism to deliver remote sensing data to users." This underscores the need for a mechanism like GEOSS to ensure data coordination and availability.

### *V.B. Strengths and Opportunities*

Given the constant development of new instruments, there are unprecedented opportunities to develop biodiversity conservation applications. De Sherbinin *et al.* (2002a) outline a number of areas in which remote sensing can be useful for environmental agreements:

- Negotiation phase: Remote sensing can help to define an environmental problem's scope and characteristics with greater accuracy so that Parties to an agreement can better define their political responses.
- Environmental assessment: Environmental assessments rely heavily on accurate, high-quality data on environmental trends and conditions. Remotely sensed data are already part of many assessments such as the Millennium Ecosystem Assessment (e.g., Lepers *et al.* 2005). Greater use of remote sensing can enhance assessment of regime impacts.
- Implementation review: By providing richer and more accurate data, remote sensing can improve review processes. The typical review of national reports is cursory, and reported data are taken at face value, but review is becoming more intensive in several environmental agreements. Remotely sensed data can help governments improve their national reports.
- Compliance and dispute resolution: Data on noncompliance can be used in a cooperative spirit to assist the noncompliant state in evaluating the causes of noncompliance and in developing remedies. Lack of capacity is often a reason for noncompliance, and better environmental data may help states coordinate and target their treaty-related expenditures, thus improving compliance.
- Broader political process: Many analysts point to the democratization of remote sensing as one of the most important impacts of the commercialization of this technology (Dehqanzada and Florini 2000). The widespread availability of image-based data may prove particularly salient to the general public (as described below).

Although it has not been a major focus of this report, it is clear that RS imagery can play a role in the political process by communicating environmental problems to the general public and decision makers in a way that increases the salience of a given issue, in much the same way that the poaching of charismatic wildlife can catalyze action when shown on national television. For example, a 1988 Landsat image of the Mexican and Guatemalan borders near Guatemala's Petén region showed that the Mexican side was largely deforested, but the Guatemalan side held largely intact forest cover. The stark contrast at the border was a catalyst in promoting one of the first meetings in decades between the Mexican and Guatemalan presidents to discuss management of borderlands. This development demonstrated the potential for remote sensing to monitor large-scale changes in the regional environment and to create a situation conducive to regional environmental planning. It can be expected that remote sensing imagery will continue to play this kind of role in increasing public support for environmental protection and promoting cooperation among states.

One encouraging trend that should be highlighted is the availability of low cost data, free software tools, and a growing array of training programs that serve to dramatically reduce the costs of remote sensing for NGOs on a limited budget and developing country organizations. Landsat 7 imagery can be obtained for as low as US$50 per scene for areas in which there is significant research interest. MODIS and ASTER data can be obtained free-of-charge. There are shareware programs such as Multispec and OpenEV that permit image processing. More information on remote sensing shareware, tutorials, and low cost imagery can be obtained through the American Museum of Natural History's Remote Sensing Resources Page (see Annex 3).

Remote sensing products can provide important information on the status and trends in land cover of biodiversity-rich areas. They can contribute to scientific assessments under the aegis of multilateral treaties, such as the recently completed Millennium Ecosystem Assessment. They can help to identify important transboundary areas in need of conservation. Notwithstanding its role in raising public awareness, data and imagery from remote sensing cannot create the political will among Parties to an agreement to ensure that the provisions of a given treaty are implemented. This is the realm of politics – and it is striking to note that the most optimistic assessments of remote sensing for treaty implementation and environmental protection tend to come from those on the technical side of the spectrum, who have less familiarity with the ins and outs of political processes (contrast, for example, Kline and Raustiala 2000 with Kuriyama 2005 and Foody 2003). Yet, as long as scientific data are given any credence in the political arena, there is hope that remote sensing can have an impact at levels ranging from the local to the global.

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# ANNEX 1. GLOBAL ECOSYSTEM AND BIODIVERSITY AGREEMENTS

This annex provides a description of global ecosystem management and biodiversity treaties, a list of the provisions (or articles) within those treaties for which remote sensing might provide useful data, and some sample applications of remote sensing that address those treaty provisions. Annex 2 provides the same information for regional agreements.

### *A1.A. Convention on Biological Diversity*

**History:** The UN Convention on Biological Diversity (CBD) was negotiated in response to global biodiversity loss, which is a significant threat facing the global environment. It was opened for signature at the United Nations Conference on the Environment and Development (UNCED) in June of 1992.

**Objectives:** The conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits arising from the utilization of genetic resources, including by appropriate access to genetic resources and by appropriate transfer of relevant technologies, taking into account all rights over those resources and technologies, and by appropriate funding.

**Implementation:** Each state that joins the Convention must report what it has done to implement the accord, and how effective that state has been in meeting the objectives of the Convention. These reports are submitted to the Conference of the Parties (COP), and are one of the primary tools for tracking progress in meeting the objectives of the Convention. COPs take place approximately every other year; as of 2005 seven COPs have been held. Incentives for compliance include enlightened self-interest, pressure and encouragement from other states, and public opinion. In addition, the Convention created several mechanisms to offer scientific expertise and support to states. The Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) is a committee composed of experts from member governments competent in relevant fields that plays a key role in making recommendations to the COP; an internet-based clearinghouse promotes the free exchange of technical information; and the Secretariat organizes meetings, drafts documents, assists member states with the implementation of treaty objectives, collects and disseminates data, and coordinates with other international organizations.

**Effectiveness:** The CBD sets broad goals and provides guidance by stating what policies governments need to pursue in order to achieve these goals. However, the emphasis of the Convention is focused on action at the national level, and the power to implement the Convention ultimately rests in the hands of individual governments.[15] Despite being a general agreement, though, 187 states have signed the Convention to date, 168 of which have ratified it. Finally, it is worth noting that a major conservation organization, the IUCN, derives its mission statements from the CBD, and that its COPs and SBSTTA meetings have become significant venues for global dialogue and scientific exchange on biodiversity conservation.

[15] http://www.plant-talk.org/Pages/cbd11.html (accessed July 2003)

In 2002, the sixth COP adopted the Strategic Plan for the Convention on Biological Diversity (Decision VI/26).[16] In its mission statement, Parties committed themselves to a more effective and coherent implementation of the three objectives of the Convention, to achieve by 2010 a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on earth. In 2004, the COP adopted a framework to facilitate the assessment of progress towards 2010 and communication of this assessment, to promote coherence among the programmes of work of the Convention and to provide a flexible framework within which national and regional targets may be set, and indicators identified (Decision VII/30).[17]

The framework includes seven focal areas. The Conference of the Parties identified indicators for assessing progress towards, and communicating the 2010 target at the global level. Two of the global indicators – *trends in extent of selected biomes, ecosystems and habitats* and *connectivity/fragmentation of ecosystems* – rely heavily on remote sensing. Parties to the Convention are invited to establish their own targets and identify indicators, within the same flexible framework.

*Analysis of the Treaty Text with Respect to Remote Sensing*

The CBD contains 42 articles without any explicit punitive measures designed to enforce compliance. The text of the Convention does not refer directly to remote sensing data, though future COPs might decide to adopt measures that involve the use of such data. There are a number of articles that involve information collection that could be obtained in a reliable and comparatively cheap manner using remote sensing data:

> <u>Article 6: General Measures for Conservation and Sustainable Use</u>
> Each Contracting Party shall, in accordance with its particular conditions and capabilities: (a) Develop national strategies, plans or programmes for the conservation and sustainable use of biological diversity or adapt for this purpose existing strategies, plans or programmes which shall reflect, *inter alia*, the measures set out in this Convention relevant to the Contracting Party concerned; and (b) Integrate, as far as possible and appropriate, the conservation and sustainable use of biological diversity into relevant sectoral or cross-sectoral plans, programmes, or policies.
>
> <u>Article 7: Identification and Monitoring</u>
> Each Contracting Party shall… (a) Identify components of biological diversity important for its conservation and sustainable use having regard to the indicative list of categories set down in Annex I; (b) Monitor, through sampling and other techniques, the components of biological diversity identified pursuant to subparagraph (a) above… (c) Identify processes and categories of activities which have or are likely to have significant adverse impacts on the conservation and sustainable use of biological diversity, and monitor their effects through sampling and other techniques…

In their Second National Reports, Parties were asked to address the question "Is your country using rapid assessment and remote sensing techniques?" in the context of Article 7. According to

[16] http://www.biodiv.org/decisions/default.aspx?m=COP-06&id=7200&lg=0 (accessed November 2005)
[17] http://www.biodiv.org/decisions/default.aspx?m=COP-07&id=7767&lg=0 (accessed November 2005)

the CBD's National Reports Analyzer[18], 10 parties replied "no", 23 parties indicated that they were exploring opportunities to do so, 58 parties replied that they were using it to a limited extent, and 13 Parties replied "yes, to a major extent." A number of those countries that responded yes, however, reported that their response applied to rapid assessment techniques and not remote sensing. A search of all reports by the Parties on the term "remote sensing" yielded a results set of 50 different reports.

In relation to Article 7(c), Geist and Lambin (2002 and 2001) undertook a meta-analysis of numerous case studies to examine the primary determinants of deforestation in many locations around the world. The meta-analysis examined 152 sub-national case studies – 78 from Latin America, 55 from Asia, and 19 from Africa – covering a time period from 1880 to 1996, with the majority of case studies falling in the fifty year period from 1940 to 1990. Many of the original studies relied on remote sensing analysis. The study focused on four proximate causes: infrastructure extension, agricultural expansion, wood extraction, and other causes (e.g., predisposing environmental factors, biophysical factors, and social disruptions such as war and population displacements). These, in turn, were related to a number of underlying drivers which were subdivided into demographic, economic, technological, policy, institutional, and cultural factors. What the meta-analysis revealed was that tropical deforestation is driven by identifiable regional patterns of causal factor synergies, of which the most prominent are economic factors, institutions, national policies and remote influences (at the underlying level) driving agricultural expansion, wood extraction, and infrastructure extension (at the proximate level).

Habitat fragmentation is one of the major contributions to biodiversity loss, and radar sensors can be used to monitor it. The TREES project, established in 1990, is a joint collaboration between the European Union and the European Space Agency (Malingreau *et al.* 1995). Its specific objectives include the compilation of a pan-tropical forest map with a scale of 1:1,000,000. The five classes of land cover used are dense and fragmented evergreen forest, dense and fragmented seasonal forest and non-forest. One of the main objectives of the project was to assess the usefulness of new sensors for tropical forest mapping, in particular the Synthetic Aperture Radar (SAR) flown aboard the ERS-1 satellite. The project demonstrated the value of radar imagery for remote sensing in areas covered by cloud and in combining the radar imagery with more traditional optical remote sensing data sources.

> <u>Article 8: In-Situ Conservation</u>
> Each Contracting Party shall, as far as possible and as appropriate: (a) Establish a system of protected areas… where special measures need to be taken to conserve biological diversity; (b) Develop… guidelines for the selection, establishment, and management of protected areas… (c) regulate or manage biological resources important for the conservation of biological diversity whether within or outside protected areas, with a view to ensuring their conservation and sustainable use… (e) promote… sustainable development in areas adjacent to protected areas with a view to furthering protection of these areas; (f) 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… (h) prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species… (l) Where a significant adverse effect on biological diversity has been determined pursuant to Article 7, regulate or manage the relevant processes and categories of activities…

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[18] http://www.biodiv.org/reports/analyzer.aspx (accessed November 2005)

As described in Section IV.D, an effective system for mapping and monitoring critical habitats for protection and management would make use of RS data. In addition, remote sensing could be used to monitor rates of development near protected areas, as well as the rate at which a degraded ecosystem recovers by monitoring rates of fragmentation, which is useful for safeguarding the in-situ conservation of ecosystems.

### *A1.B. Convention to Combat Desertification*

**History:** Desertification was discussed during the UNCED preparatory process, but before a convention could be negotiated, the General Assembly first had to establish an intergovernmental negotiating committee (INCD). Upon establishment, the INCD adopted the Convention to Combat Desertification (CCD) in June of 1994. It opened for signature in Paris on October of 1994, and it entered into force after its 50th ratification in 1996. Today the CCD is comprised of 191 member countries.

**Objectives:** The goals of the CCD are to combat desertification and mitigate the effects of drought in countries experiencing serious drought and/or desertification. These objectives are to be consistent with Agenda 21, met through effective action at all levels, supported by international cooperation and partnership arrangements, and developed in a manner that promotes sustainable development in affected areas.

**Implementation:** The Convention is implemented through national and regional action programmes to combat desertification. These action programmes are to be developed by national governments in close cooperation with donors, local populations and non-governmental organizations (NGOs). This convention is notable for its approach in recognizing the physical, biological and socio-economic aspects of desertification; the importance of redirecting technology transfer so that it is demand driven; and the involvement of local populations in the development of national action programmes.[19]

*Analysis of the Treaty Text with Respect to Remote Sensing*

The Contention to Combat Desertification contains 42 articles and does not include any explicit punitive measures designed to enforce compliance. In addition, the text of the Convention refers directly to the collection and sharing of remote sensing data as an effective way of monitoring progress.

> <u>Article 2: Objective</u>
> (1) The objective of this Convention is to combat desertification and mitigate the effects of drought in countries experiencing serious drought and/or desertification, particularly in Africa, through effective action at all levels, supported by international cooperation and partnership arrangements, in the framework of an integrated approach which is consistent with Agenda 21, with a view to contributing to the achievement of sustainable development in affected areas; (2) Achieving this objective will involve long-term integrated strategies that focus simultaneously, in affected areas, on improved productivity of land, and the rehabilitation, conservation and

[19] http://www.iisd.ca/linkages/download/pdf/enb0401-99/enb0477e.pdf (accessed July 2005).

> sustainable management of land and water resources, leading to improved living conditions, in particular at the community level.

See examples of remote sensing applications for measuring biodiversity richness and habitat loss in arid and semi-arid environments from Sections IV.A. and IV.C. In a study by Lenney and Woodcock (1996) field-calibrated, multi-temporal NDVI features derived from ten Landsat TM images dating from 1984 to 1993 were used to assess the status of agricultural lands in the Nile Delta and adjacent Western Desert and coastal regions. The results indicate that 3.74% of agricultural land in the Delta has reduced productivity. In addition, the high overall accuracy of the map (95.85%) supports the use of multi-temporal features in mapping the status of agricultural lands.

Similarly, in San Luis Province, Argentina, two Landsat images from 1982 and 1992 were used to emphasize degraded areas.[20] Desertification was determined by subjecting the images to geometric and radiometric correction as well as multi-temporal comparison techniques. Spectral un-mixing of the vegetation, water and sand components facilitated the analysis of areas of heterogeneous cover from the satellite images. Simple differences between unmixed images of sand or water revealed dune movement, re-vegetation trends and variations in water bodies as a result of changing rainfall and land use patterns; these results demonstrate how remote sensing can be used to monitor desertification

> <u>Article 3: Principles</u>
> In order to achieve the objective of this Convention and to implement its provisions, the Parties shall be guided, *inter alia*, by the following: …(b) the Parties should… improve cooperation and coordination at subregional, regional and international levels, and better focus financial, human, organizational and technical resources where they are needed…

Remote sensing allows for increased cooperation between parties because information can be shared in consistent formats across borders (e.g. digital images) against which ecosystem changes are monitored.

> <u>Article 5: Obligations of affected country Parties</u>
> In addition to their obligations pursuant to article 4, affected country Parties undertake to: …(b) establish strategies and priorities, within the framework of sustainable development plans and/or policies, to combat desertification and mitigate the effects of drought… (d) promote awareness and facilitate the participation of local populations, particularly women and youth, with the support of non-governmental organizations, in efforts to combat desertification and mitigate the effects of drought.

Remote sensing could be used to monitor the effectiveness of a given strategy to reclaim or improve degraded lands (e.g., dune stabilization measures), and to identify factors that hamper the success of these strategies. In addition, remote sensing technology could be used to foster public support for sustainable development measures by showing the public through maps created from remotely sensed data the amount of usable land lost to desertification.

[20] http://www.geogra.uah.es/Personal/emilio.chuvieco/collado2002.pdf (accessed June 2003).

> Article 6: Obligations of developed country Parties
> In addition to their general obligations pursuant to article 4, developed country Parties undertake to: … (e) promote… access by affected country Parties, particularly affected developing country Parties, to appropriate technology, knowledge and know-how.

Capacity building in remote sensing technologies is already taking place through multiple programs. Although costs of imagery can sometimes be prohibitive, training government agency staff to monitor land cover changes using remotely sensed data combined with selective ground truthing would still be significantly more cost effective than aerial surveillance or ground-based measures of land degradation.

> Article 8: Relationship with other conventions
> …The Parties shall encourage the conduct of joint programmes, particularly in the fields of research, training, systematic observation and information collection and exchange, to the extent that such activities may contribute to achieving the objectives…

Article 8 specifically refers to "systematic observation," and acknowledges its potential for serving as a very useful tool in achieving the objectives of the Convention.

> Article 10: National action programmes
> (1) The purpose of national action programmes is to identify the factors contributing to desertification and practical measures necessary to combat desertification and mitigate the effects of drought… (4) Taking into account the circumstances and requirements specific to each affected country Party, national action programmes include… sustainable management of natural resources; sustainable agricultural practices… strengthening of capabilities for assessment and systematic observation, including hydrological and meteorological services, and capacity building, education and public awareness.

This article states that remote sensing – or "meteorological services" – could be useful for implementing national action programs as an effective way to monitor factors that might aggravate the desertification problem, such as unsustainable agricultural development.

> Article 16: Information collection, analysis and exchange
> The Parties agree, according to their respective capabilities, to integrate and coordinate the collection, analysis and exchange of relevant… information to ensure systematic observation of land degradation in affected areas and to understand better and assess the processes and effects of drought and desertification… To this end, they shall, as appropriate: (A) facilitate and strengthen the functioning of the global network of institutions and facilities for the collection, analysis and exchange of information, as well as for systematic observation at all levels, which shall, *inter alia*: (i) aim to use compatible standards and systems; (ii) encompass relevant data and stations, including in remote areas; (iii) use and disseminate modern technology for data collection, transmission and assessment on land degradation; and (iv) link national, subregional and regional data and information centres more closely with global information sources…

Again, the Convention alludes to the effectiveness of remote sensing technology for the "systematic observation" of problems relevant to the treaty and to monitor activities that might threaten the goals of the treaty. A CCD booklet on Early Warning Systems (EWSs) addresses the use of remote sensing, with a case study on a remote sensing application for the monitoring of desertification processes in the Mediterranean Basin.[21] According to this booklet: "The primary data used for desertification monitoring and drought early warning on a small scale are rainfall measurements and the remote sensing-derived Normalized Difference Vegetation Index (NDVI)… [I]t was recognized that desertification monitoring requires the systematic tracking of land conditions, work not undertaken by most drought EWSs and which the older generation of satellites do not sufficiently cover" (p. 22).

> Article 19: Capacity building, education and public awareness
> The Parties recognize the significance of capacity building… in efforts to combat desertification and mitigate the effects of drought… (3) The Parties shall cooperate… in undertaking and supporting public awareness and educational programmes… to promote understanding of the causes and effects of desertification… and of the importance of meeting the objective of this Convention. To that end, they shall: (a) organize awareness campaigns for the general public; (b) promote… access by the public to relevant information, and wide public participation in education and awareness activities…

Satellite images could be used to illustrate the actual threat of desertification and drought because changes to a base map are relatively easy to communicate to the general public. For example, a report in *Science* by Tucker *et al.* (1991), based on NDVI calculated from AVHRR imagery, raised concern about desertification by reporting on the expansion of the Sahara Desert from 1980 to 1990. The researchers found that the southern boundary of the Sahara had moved 130 kilometers south during this period, and that the overall extent of the Sahara had increased by 1.3 million $km^2$.

### *A1.C. Convention on Migratory Species*

**History:** The Convention on the Conservation of Migratory Species of Wild Animals (referred to as the Bonn Convention or CMS) entered into force on November 1, 1983, following the sudden realization of the rapid decline in migratory animal populations and migratory animal habitats.

**Objectives:** The Convention on the Conservation of Migratory Species of Wild Animals (also known as the Bonn Convention) aims to conserve migratory animal species throughout their range. Parties to the Convention work together in order to conserve migratory species and their habitats by providing strict protection for endangered migratory species, by concluding multilateral agreements for the conservation and management of migratory species, and by undertaking co-operative research activities.

**Implementation:** A Secretariat under the auspices of the United Nations Environment Programme (UNEP) provides administrative support to the Convention. The decision-making organ of the Convention is the Conference of the Parties (COP). COPs have been held every three years since the treaty entered into force, and the Convention has had seven conferences so far, with the 8th scheduled for November 2005 in Nairobi, Kenya. In addition, a Standing Committee provides policy and administrative guidance between regular meetings of the COP. A

[21] http://www.unccd.int//cop/cst/adhocpanel/booklet_EWS.pdf (accessed November 2005)

Scientific Council consisting of experts appointed by individual member States and by the COP, gives advice on technical and scientific matters.[22] The Convention includes two appendices: Appendix I lists endangered species; Appendix II lists "species which have an unfavourable conservation status and which require international agreements for their conservation;" Many migratory bird and mammal species are in CMS Appendices I and II.

*Analysis of the Treaty Text with Respect to Remote Sensing*

Article III: Endangered Migratory Species: Appendix I

(2) A migratory species may be listed in Appendix I provided that reliable evidence, including the best scientific evidence… indicates… the species is endangered.
(3) A migratory species may be removed from Appendix I when the COPS determines that: (A) reliable evidence including the best scientific evidence available, indicates that the species is no longer endangered, and (B) the species is not likely to become endangered again because of loss of protection due to its removal from appendix I.
(4) Parties that are Range States… species listed in Appendix I shall endeavour: (A) to conserve and, where feasible and appropriate, restore those habitats of the species which are of importance in removing the species from danger of extinction; (B) to prevent, remove, compensate for or minimize… the adverse effects of activities or obstacles that seriously impede or prevent the migration of the species…

Though remotely sensed data is not explicitly mentioned here, it is clear that this article requires both the creation of habitat suitability maps and the monitoring of critical habitat. These types of maps can be created by identifying vegetation maps using satellite data and evaluating habitat preference and conditions of wildlife species based on information obtained through field data. Tamura and Higuchi (2000) used Landsat TM data to investigate the habitat of two migratory birds, the red crowned cranes and oriental white storks, in East Asian wetlands. By combining satellite tracking and Landsat TM data, they analyzed the relationship between ground conditions and habitat patterns of these species, and successfully identified the habitat preferences of these two birds. For further examples, see Section A1.D on the Ramsar convention which addresses comparable issues.

Article V: Guidelines for Agreements

(1) The object of each Agreement shall be to restore the migratory species concerned to a favourable conservation status or to maintain it in such a status. Each Agreement should deal with those aspects of the conservation and management of the migratory species concerned which serve to achieve that object.
(2) Each Agreement should cover the whole of the range of the migratory species concerned and should be open to accession by all Range States of that species, whether or not they are Parties to this Convention.
(4) Each Agreement should… (D) Establish… machinery to assist in carrying out… the Agreement, to monitor its effectiveness, and to prepare reports for the COPs…
(5) Where appropriate and feasible, each Agreement should provide for but not be limited to: (A) periodic review of the conservation status of the migratory

[22] http://www.wetlands.org/networks/partners.htm#Bonn (accessed June 2003).

> species concerned and the identification of the factors which may be harmful to that status; (B) coordinated conservation and management plans; (C) research into the ecology and population dynamics of the migratory species concerned, with special regard to migration… (E) conservation and, where required and feasible, restoration of the habitats of importance in maintaining a favourable conservation status, and protection of such habitats from disturbances… (F) maintenance of a network of suitable habitats appropriately disposed in relation to the migration routes; (G) where it appears desirable, the provision of new habitats favourable to the migratory species or reintroduction of the migratory species into favourable habitats; (H) elimination of, to the maximum extent possible, or compensation for activities… which hinder… migration; (I) prevention, reduction or control of the release into the habitat of the migratory species of substances harmful to that migratory species… exchange of information on substantial threats to the migratory species; (N) making the general public aware of the contents and aims of the Agreement.

The establishment of a four-million acre biosphere reserve between Mexico and Guatemala was established “in part due to evidence of tropical forest destruction gained through satellite data” (Kline and Raustiala 2000). The data showed how the Mexican side was largely deforested, while the Guatemalan side remained forested. The contrast at the border, clearly visible in a Landsat image, led to the first meetings between the presidents of both states to discuss borderland management. Interpretation of 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. The meetings contributed partially to the establishment of the Meso-American Biological Corridor, which is a combination of protected areas and managed landscape that forms a continuous wildlife migration route from Panama to Mexico. This Corridor combines sustainable use of biodiversity within the framework of sustainable development.

The integration of remote sensing land cover maps and data from GPS or radio-collared animals in a GIS environment can lead to highly useful information on animal migration patterns, and ultimately contribute to conservation efforts. The Brazilian Institute for Ecological Research (IPE) has conducted GIS and remote sensing studies of remaining habitat in the biodiverse Mata Atlantica of eastern Brazil to establish wildlife migration corridors. IPE has been reforesting pilot areas of land with the help of small landholders. Using information gleaned from the radio-tagged animals, the farmers help create protected wildlife corridors, planted with native trees. The farmers then began planting 50m-wide belts of native trees around the edges of existing forest patches to provide a buffer zone against the damaging weed invasions. They are also planting new patches of native trees that increase connections between forest fragments and provide shade for crops such as coffee.[23]

> <u>Article VII</u>
>
> (5) At each of its meetings the COPS shall review the implementation of this Convention and may in particular: (a) review and assess the conservation status of migratory species; (b) review the progress made towards the conservation of migratory species, especially those listed in Appendices I and II… (e) make recommendations to the Parties for improving the conservation status of migratory species and review the progress being made under

[23] http://www.sciencealert.com.au/features/forest.htm (accessed July 2005).

> Agreements; (f) in those cases where an Agreement has not been concluded, make recommendations for the convening of meetings of the Parties that are Range States of a migratory species… to discuss measures to improve the conservation status of the species; (g) make recommendations… for improving the effectiveness of this Convention.

Remote sensing is useful in carrying out the goals of this article, since it is a useful tool for identifying and monitoring problems and the conservation status of various species and their habitats.

### *A1.D. Ramsar Convention on Wetlands of International Importance*

**History:** The initial call for an international convention on wetlands came in 1962 during a conference which formed part of Project MAR, a program established in 1960 following concern at the rapidity with which large stretches of marshland and wetlands in Europe were being destroyed, with a resulting decline in numbers of waterfowl. Finally, at an international meeting at Ramsar, Iran, the text of the Convention was agreed on 2 February 1971 and signed by the delegates of 18 nations the next day. The Convention entered into force in December 1975, upon receipt by UNESCO, the Convention Depositary, of the seventh instrument of accession to or ratification of the Convention, which came from Greece. The Convention celebrated its 25th anniversary in 1996 and now has 138 Contracting Parties from all regions of the world. Since its adoption, the Convention has been modified on two occasions – by a protocol in 1982, and by amendments to the original treaty, known as the Regina Amendments of 1987, to stem the progressive encroachment on and loss of wetlands now and in the future.

**Objectives:** The goal of the Convention is the "conservation and wise use of wetlands by national action and international cooperation as a means to achieving sustainable development throughout the world." Each contracting party must place at least one wetland site on the Ramsar List and promote its conservation.

**Implementation:** Each contracting party to the Ramsar Convention designates an agency within its government to take responsibility for the implementation of the Convention. Every three years there is a Convention of Parties, which meets in order to decide on policy in the coming period.

**Effectiveness:** Because all Parties are required to nominate at least one wetland site, the convention has been effective in protected these sites, though its impact on wetlands more broadly is harder to determine. The Montreux Record is the equivalent to an "endangered wetlands" list, and serves as a means of leverage over parties that have committed certain wetland sites to long-term conservation by adding them to the Ramsar list.

*Analysis of the Treaty Text with Respect to Remote Sensing*

The Ramsar Convention contains 12 articles and does not include any explicit punitive measures to enforce compliance. Though the treaty text makes no mention of remote sensing, some articles that require the collection of information refer to data that could be collected in an efficient way using RS. Information for this section is based in part on a report by Atlantis Scientific (2002). Further information may be gleaned from the Ramsar Remote Sensing Case Studies.[24]

[24] http://sedac.ciesin.columbia.edu/ramsardg/casestudies (accessed July 2005).

> Article 2
> (1) Each Contracting Party shall designate suitable wetlands within its territory for inclusion in a List of Wetlands of International Importance, hereinafter referred to as "the List…" The boundaries of each wetland shall be precisely described and also delimited on a map and they may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands, especially where these have importance as waterfowl habitat… (6) Each Contracting Party shall consider its international responsibilities for the conservation, management and wise use of migratory stocks of waterfowl, both when designating entries for the List and when exercising its right to change entries in the List...

*Wetland delimitation*: In an early application of relevance to the Ramsar convention, multispectral scanner (MSS) imagery of Savannah River non-tidal wetlands were analyzed by Jensen *et al*. (1984) to find bands useful for discriminating among wetland inventory classes, where the classes cluster, and what wetland classification accuracies can be expected. Emergent marsh, scrub-shrub, mixed deciduous swamp forest, and mixed deciduous upland forest were found to cluster in somewhat predictable regions of 2- and 3-dimensional feature space. The classification accuracy of the delta study area was about 83% and was assessed by comparing the remote sensing derived thematic map with 1,325 linear meters of transects sampled in situ. These results suggest that high-resolution aircraft MSS data can provide detailed vegetation type information for mapping both thermally affected and rejuvenating nontidal wetland in the South Carolina Savannah River Swamp System.

*Wetlands Monitoring*: Haddad and McGarry (cited in Atlantis Scientific 2002, p. 59) used Landsat TM to map and monitor Florida's coastal ecosystem. After processing the data into 256 classes using red, green, and near infrared bands and performing geo-correction, they did a trend analysis by merging historical results interpreted from aerial photos with the TM images. An early study by Wickware and Howarth (1981) examined the Peace-Athabasca Delta in Canada, which has experienced major changes in water boundaries and vegetation types due to flooding. The team made comparisons of parts of the delta under normal and flooded conditions. The team effectively determined that Landsat digital data was capable of monitoring such changes.

*Coral Reef Monitoring*: Hochberg and Atkinson (2003) investigated the abilities of seven sensors to classify coral, algae, and carbonate sand based on reflectance spectra measured in situ on reefs around the world. They assessed the spectral capabilities of the sensors by applying to the in situ spectra the spectral responses of two airborne hyperspectral sensors (AAHIS and AVIRIS), three satellite broadband multispectral sensors (Ikonos, Landsat ETM+ and SPOT-HRV), and two hypothetical satellite narrow band multispectral sensors (Proto and CRESPO). Classification analyses of the simulated sensor-specific spectra produce overall accuracy rates of 98%, 98%, 93%, 91%, 64%, 58%, and 50% for AAHIS, AVIRIS, Proto, CRESPO, Ikonos, Landsat-ETM+, and SPOT-HRV, respectively. Analyses reveal that the hyperspectral and narrowband multispectral sensors can discriminate between coral and algae across many levels of mixing.

*Mangrove Monitoring*: Seto and Fragkias (2005) explicitly tested the effectiveness of the Ramsar Convention in preventing conversion of a mangroves to aquaculture at two Ramsar sites (and nature reserves) in the Red River delta of Vietnam. They utilized Landsat imagery from 1975 to 2002 covering the delta together with ground surveys. Results suggest that the Ramsar site designation, which was established in 1989, initially did not slow mangrove loss at the sites, but that between 1992 and 2002 there was a slow but steady increase in mangrove extent, from 10 $km^2$ to 24 $km^2$, though still shy of the 36 $km^2$ in mangrove area registered in 1986. Given the high level of fragmentation and serious impacts of aquaculture on biogeochemical processes, they conclude, however, that despite these modest increases in mangrove area, aquaculture activities at these sites do not meet the criteria of "wise use" as described in the convention text.

Between the late 1980s and early 1990s, significant sections of the Belizean coast came under escalating pressure from development. Murray *et al*. (2003) assessed characteristics of the country's remaining mangroves. GIS analysis of 1990 Landsat TM remote sensing data reveals that Belize's mangrove cover 78,511 ha, equivalent to 3.4% of the country's land area and approximately 2% of the mangrove remaining in the Americas. Through the examination of early aerial photos, historical records and ground conditions, by 1990 about 98% of Belize's original mangrove cover (80,016 ha) remained. However, more recent mapping for the Belize City area, using 1992 aerial photos, reveals that a further 519 ha has been cleared, a 0.7% reduction in the national total in just two years.

*Land Cover Changes*: Arzandeh and Wang used Landsat TM for vegetation change detection in an Ontario wetland using classification methods. Methods were improved when information was introduced into the classification process, and the presence of the mid-infrared band in Tm data was important in their success (in Atlantis Scientific p. 61). Also, Houhoulis and Michener used SPOT-XS imagery to detect wetland change. An unsupervised classification produced 20 classes, which were aggregated into six broad land cover classes, and found that 8 percent of wetlands had undergone change. While highly accurate, the methods involved here are labor intensive and require technological information that might not be available in developing nations (in Atlantis Scientific 2002, p. 62).

*Land Use Changes*: Tappan *et al.* (2000) monitored land use changes in Senegal near Ramsar Wetland Delta du Saloum. Due to declassification of Corona and Argon satellite imagery by the intelligence community, a new source of old data surfaced and imagery was acquired from as early as 1962 in Senegal, and compared to newer 1992 Landsat TM imagery Findings showed a significant amount of change has taken place in the region since 1984 when the wetland was designated a Ramsar site. Of particular importance to the Delta du Saloum wetland are the upstream changes that impact the wetland – for example, almost all of the woodland areas have disappeared next to the delta, but within the mangrove and savanna forests there has been little or no change.

> <u>Article 3</u>
> (1) The Contracting Parties shall formulate and implement their planning so as to promote the conservation of the wetlands included in the List, and as far as possible the wise use of wetlands in their territory. (2) Each Contracting Party shall arrange to be informed at the earliest possible time if the ecological character of any wetland in its territory and included in the List has changed, is changing or is likely to change as the result of technological developments, pollution or other human interference. Information on such changes shall be passed without delay to the organization or government responsible for the continuing bureau duties specified in Article 8.

Frequent monitoring of wetlands sites using remote sensing can enable states to detect early changes efficiently. EarthSat Corportation conducted a study of land cover changes in the Chesapeake Bay that utilized Cross-Correlation Analysis to identify wetland losses.[25]

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[25] http://sedac.ciesin.columbia.edu/ramsardg/casestudies/earthsat.html (accessed on November 11, 2005)

> Article 4
> (1) Each Contracting Party shall promote the conservation of wetlands and waterfowl by establishing nature reserves on wetlands, whether they are included in the List or not, and provide adequately for their wardening. (2) Where a Contracting Party in its urgent national interest, deletes or restricts the boundaries of a wetland included in the List, it should as far as possible compensate for any loss of wetland resources, and in particular it should create additional nature reserves for waterfowl and for the protection, either in the same area or elsewhere, of an adequate portion of the original habitat. (3) The Contracting Parties shall encourage research and the exchange of data and publications regarding wetlands and their flora and fauna. (4) The Contracting Parties shall endeavour through management to increase waterfowl populations on appropriate wetlands.

Tracking wetland size and extent, as well as land use changes, within official Ramsar site boundaries could enable Parties or NGOs to identify significant changes in the original character or extent of the wetland, and to notify the secretariat. Such losses could then be replaced elsewhere by nature reserves in similar habitats.

> Article 5
> The Contracting Parties shall consult with each other about implementing obligations arising from the Convention especially in the case of a wetland extending over the territories of more than one Contracting Party or where a water system is shared by Contracting Parties. They shall… endeavour to coordinate and support present and future policies… concerning the conservation of wetlands and their flora and fauna.

In this case, remote sensing has the potential to monitor the efficacy of state coordination. In addition, it allows for the exchange of data through a through a common map.

### *A1.E. World Heritage Convention*

**History:** The Convention Concerning the Protection of the World Cultural and Natural Heritage (the World Heritage Convention or WHC) was adopted by the General Conference of UNESCO in 1972. The World Heritage Committee was formed in 1976 to implement the Convention Concerning the Protection of the World Cultural and Natural Heritage (World Heritage Convention) adopted in 1972 by the 17th UNESCO Conference. This committee is responsible for determining which natural and cultural areas should be protected under the World Heritage Convention. As of January 2004, there were 754 sites (known by the WHC as “properties”) were included on the World Heritage List, including 582 cultural sites, 149 natural sites, and 23 sites that represent a combination. The convention has 129 Parties.

**Objectives:** The goals include the establishment of an effective system of collective identification, protection, and preservation of cultural and natural heritage around the world considered to be of outstanding universal value.  This includes providing both emergency and long-term protection for monuments, groups of buildings, and sites with historical, aesthetic, archaeological, scientific, ethnological, or anthropological value, as well as outstanding physical, biological, and geological formations, habitats of threatened species of animals and plants, and areas with scientific, conservation, or aesthetic value.

Article 8 establishes the World Heritage Committee as a Bureau within UNESCO. This Committee is made up of 21 representatives elected from the 142 member nations. Three other representatives fill seats on the committee. These include a representative from the IUCN, a representative from the International Centre for the Study of the Preservation and Restoration of Cultural Properties (Rome Centre), and one representative from the International Council of Monuments and Sites (ICOMOS). In addition to having the capacity of holding seats on the World Heritage Committee itself, it is also important to note that the Director-General of UNESCO is directed under Article 14 of the Convention to utilize "to the fullest extent possible the services" of these three organizations. The World Heritage Committee has two major functions. The first function is to administer the World Heritage Fund, to determine how money should be allocated to countries and organizations that request assistance. The second function is to define World Heritage, which involves selecting cultural and natural wonders. The International Council on Monuments (ICOMOS) and the IUCN, which examine the proposals of different countries and draw up evaluation reports on each proposal, help the Committee in this function.

**Effectiveness:** In the 25 years since the Convention's inception, there have been changes in its operational emphasis. In particular, there is an increasing emphasis upon monitoring the state of conservation of the properties on the list, in addition to the identification of new world heritage sites. The processes of evaluating site nominations for the list have become increasingly rigorous.

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article 2
> …The following shall be considered as "natural heritage:" natural features consisting of physical and biological formations… which are of outstanding universal value from the aesthetic or scientific point of view; geological and physiographical formations and precisely delineated areas which constitute the habitat of threatened species of animals and plants of outstanding universal value from the point of view of science or conservation; natural sites or precisely delineated natural areas of outstanding universal value from the point of view of science, conservation or natural beauty.

Remote sensing assisted mapping would help to delineate the natural features that require protection, as well as permitting monitoring of the area to make sure it is safeguarded.

> Article 5
> To ensure that effective and active measures are taken for the protection, conservation and presentation of the cultural and natural heritage situated on its territory, each State… shall endeavor, in so far as possible, and as appropriate for each country: …(b) to set up within its territories, where such services do not exist, one or more services for the protection, conservation and presentation of the cultural and natural heritage with an appropriate staff and possessing the means to discharge their functions; (c) to develop scientific and technical studies and research and to work out such operating methods as will make the State capable of counteracting the dangers that threaten its cultural or natural heritage; (d) to take the appropriate legal, scientific, technical, administrative and financial measures necessary for the identification, protection, conservation, presentation and rehabilitation of this heritage; and (e) to foster the establishment or development of national or regional centres for training in the protection,

> conservation and presentation of the cultural and natural heritage and to encourage scientific research in this field.

Article 5 explicitly instructs states to identify and monitor relevant sites. One problem, however, is that accurate maps are not available to many states, and existing specific boundary information is often of poor quality. In order to effectively monitor and protect these sites, it is necessary to be able to detect changes in and around the site. A unit within UNESCO's WH convention secretariat is involved in the development and application of remote sensing applications for WH sites. Furthermore, a conference was organized by Eurisy in October 2003 on Use of Space Technologies for Cultural and Natural Heritage Management that addressed this topic at some length.[26]

> <u>Article 6</u>
> (1) Whilst fully respecting the sovereignty of the States on whose territory the cultural and natural heritage mentioned in Articles 1 and 2 is situated, and without prejudice to property right provided by national legislation, the States Parties to this Convention recognize that such heritage constitutes a world heritage for whose protection it is the duty of the international community as a whole to co-operate.

The Convention emphasizes the international value of identifying and monitoring World Heritage sites. Without mentioning remote sensing explicitly, this article lends some legitimacy to its use as a legitimate means of monitoring state compliance with their promise to protect world heritage sites.

> <u>Article 21</u>
> (1) The World Heritage Committee shall define the procedure by which requests to it for international assistance shall be considered and shall specify the content of the request, which should define the operation contemplated, the work that is necessary, the expected cost thereof, the degree of urgency and the reasons why the resources of the State requesting assistance do not allow it to meet all the expenses. Such requests must be supported by experts' reports whenever possible…

This article suggests that requests for international assistance must be accompanied by expert reports. Use of satellite imagery gives researchers the tools to demonstrate how a particular site is being threatened.

> <u>Article 24</u>
> International assistance on a large scale shall be preceded by detailed scientific, economic and technical studies. These studies shall draw upon the most advanced techniques for the protection, conservation, presentation and rehabilitation of the natural and cultural heritage and shall be consistent with the objectives of this Convention. The studies shall also seek means of making rational use of the resources available in the State concerned.

Again, although this section fails to mention remote sensing overtly, this section suggests that these technologies should be looked at and used if proven effective in the future.

[26] http://www.eurisy.asso.fr/ (accessed July 2005).

### *A1.F. International Plant Protection Convention*

**History:** The Convention was adopted by the U.N. Food and Agriculture Organization in 1951 and came into force in 1952. It was amended in both 1973 and 1997. The 1997 revision was done to reflect the role of the International Plant Protection Convention (IPPC) in relation to the GATT Uruguay Round Agreements, particularly the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement). The SPS Agreement identifies the IPPC as the organization providing international standards to help ensure that measures implemented to protect plant health from harmful pests are coordinated and not used as non-tariff trade barriers.

**Objective:** The goal of the IPPC is to spur participating states to take action in order to prevent the spread and introduction of pests of plants and plant products, and to promote appropriate measures for their control. The Convention extends to the protection of natural flora and plant products, and includes both direct and indirect damage by pests, including weeds.

**Implementation:** One of the main focuses of the IPPC is the establishment of international standards for phyto-sanitary measures (ISPM). The 1997 amendments established a Commission on Phyto-sanitary measures, whose functions are to review the state of plant protection globally, provide direction to the work program of the IPPC Secretariat, and approve standards. The Secretariat is responsible for coordinating the work program of the IPPC, particularly the ISPM. The IPPC also has dispute settlement provisions, and although the dispute settlement process is non-binding, the results of the process can be expected to have substantial influence in disputes that may be raised to the WTO under the SPS Agreement.

*Analysis of the Treaty Text with Respect to Remote Sensing*

> <u>Article IV: National Organization for Plant Protection</u>
> (1) Each contracting party shall make provision, as soon as possible and to the best of its ability, for (a) an official plant protection organization with the following main functions: (i) the inspection of growing plants, of areas under cultivation (including fields, plantations, nurseries, gardens and greenhouses), and of plants and plant products in storage or in transportation, particularly with the object of reporting the existence, outbreak and spread of plant pests and of controlling those pests…

Although remote sensing technology cannot directly detect the presence of plant pests, it can be used to monitor changes in spectral responses that might indicate the presence of plant pests. For example, Zhang *et al.* (2003) used hyperspectral remotely sensed data taken from low altitude flights, which has high spectral and spatial resolution, in order monitor crop disease in a diseased tomato field in California’s Salinas Valley.

### *A1.G. International Tropical Timber Agreement*

**History:** When Japan, the world's largest importer of tropical timber in terms of volume, became concerned about deforestation threatening the global timber supply, it proposed a resolution at the United Nations Conference on Trade and Development (UNCTAD) to create an International Timber Trade Organization (ITTO) in 1977, which would be strictly confined to trade considerations. However, it soon became clear that tropical timber could not be treated in such a narrowly defined manner because tropical timber comes from a wide variety of tree species, and cannot be dealt with as a single commodity. For this reason, the International Institute for Environment and Development (IIED) forcefully argued that the agreement could not be limited to the technical and commercial concerns of timber extraction and trade, but must also provide for the ecological and genetic services provided by forests. As a result, in the final stages of several years of negotiations of the ITTA, the environmental role of tropical forests came to feature rather prominently. The ITTA, signed in November 1983 after six years of protracted negotiations, thus emerged as a unique trade agreement. Environmental NGOs welcomed the ITTO, perceiving that it offered an opportunity to enforce sustainable forest management.[27]

**Objective:** To provide a framework for cooperation between countries producing and consuming tropical timber, to promote the expansion and diversification of international trade in tropical timber and the improvement of structural conditions in the tropical timber market, to promote and support research and development looking to improve forest management and wood utilization, and to encourage the development of national policies aimed at sustainable use and conservation of tropical forests and their genetic resources, and at maintaining the ecological balance in the regions concerned.

**Implementation:** The governing body of the ITTO is the International Tropical Timber Council (ITTC), which includes all 58 members. The ITTO has two categories of membership: Producer and Consumer countries. Annual contributions and votes are distributed equally between the two groups, which are called "Caucuses." Within each caucus, individual member's dues and votes are calculated based on market share, and in the case of producers, the extent of tropical forests within the state. The Council is supported by four committees, which are open to all members and provide advice and assistance to the Council on issues being considered. Three of the committees deal with policy and project work: Economic Information and Market Intelligence, Reforestation and Forest Management, and Forest Industry. An Expert Panel supports these committees and reviews project proposals for technical merit and relevance to ITTO objectives. The fourth committee, on Finance and Administration, advises the Council on budget and administrative matters. The Council and Committees are supported by a small Secretariat headed by the Executive Director, who is responsible for the administration and operation of the Agreement.[28]

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article 25: Functions of the Committees
> (1) The Committee on Economic Information and Market Intelligence shall…
> (c) Keep under continuous review the international tropical timber market, its current situation and short-term prospects on the basis of the data mentioned in subparagraph (b) above and other relevant information; … (d) Make recommendations to the Council on the need for, and nature of, appropriate studies on tropical timber, including long-term prospects of the international tropical timber market, and monitor and review any studies commissioned by the Council; (e) Carry out any other tasks related to the economic, technical and statistical aspects of tropical timber assigned to it by the Council…
> (2) The Committee on Reforestation and Forest Management shall: (a) Keep under regular review the support and assistance being provided… for… forest management for the production of industrial tropical timber… (d) Review

[27] http://www.ncseonline.org/NLE/CRSreports/Forests/for-4a.cfm?&CFID=8590460&CFTOKEN-=38049796#Origins%20of%20the%20ITTA (accessed June 2003).
[28] http://www.itto.or.jp/inside/about.html (accessed June 2003).

> regularly future needs of international trade in industrial tropical timber and, on this basis, identify and consider appropriate possible schemes and measures in the field of…forest management….
> (3) The Committee on Forest Industry shall… (c) Monitor ongoing activities in this field, and identify and consider problems and possible solutions to them …

Remote sensing can be applied in this instance to monitor sources of tropical timber, and possibly to ensure that it is being harvested in a sustainable manner. For example, methods have been developed for the detection of selectively logged forests in the Amazon using remote sensing, which is relevant to forest management issues (Souza and Barreto 2000). One program, ForestWatch, has been successfully applying remote sensing to the monitoring of tropical forest timber concessions and areas gazetted for protection.[29] RS can be used to monitor the territorial extent of the forest as well as changes inside of the forest.

De Wasseige and DeFourney (2002) used six different SPOT-HRVIR images to observe three different tropical rain forest types, and obtained texture information through geo-statistical analysis based on direction variograms for the near infra-red (NIR) band. The geometric-optical gap model they used explains more than 80% of the variability of the NIR reflectance. Finally, they proposed a cross-thresholding approach using the NIR reflectance and the Local Directional Contrast (LDC) and applied it successfully in order to discriminate the canopy roughness of the different forest sites.

> <u>Article 27: Statistics, Studies and Information</u>
> (1) The Council shall establish close relationships with appropriate… organizations… to help ensure the availability of… information on all factors concerning tropical timber…
> (2) The Council shall arrange to have any necessary studies undertaken of the trends and of short- and long-term problems of the world tropical timber market.

In response to Article 27, remote sensing could monitor short and long-term trends with respect to tropical forests.

### *A1.H. Man and Biosphere Program*

**History:** The Man and the Biosphere Program (MAB) was established by UNESCO in 1970, where the International Coordinating Council (ICC) for MAB was chartered. The biosphere reserve network, launched in 1976, has grown to include 499 reserves in 110 countries as of July 2005. The network is vital to achieving the MAB goal of achieving a sustainable balance between conserving biological diversity, promoting economic development, and maintaining associated cultural values.

**Objectives:** The goals of the MAB program are to develop the basis for the rational use and conservation of the resources of the biosphere, and for the improvement of the global relationship between people and the environment. The MAB program encourages the use of an “ecosystem approach” in guiding research and monitoring in order to facilitate their integration into effective and sustained interventions.

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[29] http://www.globalforestwatch.org/ (accessed July 2005)

**Implementation:** MAB provided the first formal mechanism for bringing together and coordinating diffuse research, conservation, and training activities through an international network of 499 biosphere reserves in 110 countries. Biosphere Reserves are multifunctional areas nominated by MAB national programs. The criteria for selection are legal protection for conservation of a core area, active scientific infrastructure, involvement of regional stakeholders, and potential to demonstrate sustainable human use of ecosystems. Currently, 125 nations participate in the MAB Program. In each country a MAB national committee defines and organizes specific national activities to be under the protection of MAB.[30]

*Analysis of the MAB Principles with Respect to Remote Sensing*

MAB is not strictly speaking a treaty but rather a site designation, so rather than analyze the treaty text the agreement is analyzed with respect to the principles of the ecosystem approach through which it operates.

> Principle 3: Ecosystem managers should consider the effects (actual or potential) of their activities on adjacent or other ecosystems.

One problem for ecosystem managers is the fact that the sustainable use of a large-scale valuable ecosystem has always been difficult in regions impacted by human activity, especially since authorities in charge of different sectors of land do not always have an overview of the whole ecosystem as an interrelated system. Remotely sensed images could provide synoptic views of the ecosystem.

> Principle 5: Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target of the ecosystem approach.

Research in the Amazon by Nepstad *et al.* (1999) on forest impoverishment, and on selective logging (Souza and Barreto 2000), is relevant to this principle. However, in general it is difficult to detect the degree of disruption to ecosystem structure and functioning from RS images alone. This principle really requires *in situ* monitoring in conjunction with remote sensing.

> Principle 7: The Ecosystem approach should be undertaken at the appropriate spatial and temporal scale.

Remote sensing data of varying spatial resolutions may help to identify the appropriate scale for conservation of a given area.

> Principle 8: Recognizing the varying temporal scales and lag effects that characterize ecosystem processes, objectives for ecosystem should be set for the long run

Satellite imagery might prove useful in this respect, since their historical archive is large. MSS images from Landsat date back to the early 1970s and TM images date back to the mid-1980s, though some imagery has undoubtedly been lost. Managers could use these archives to monitor ecosystem changes over extended periods of time and use time series images to observe long-term progress for a given ecosystem. In addition, the use of archived data could contribute to the setting of better long term objectives for management.

[30] http://members.aol.com/poesgirl/page1.htm (accessed on November 11, 2005)

> Principle 10: The ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations, and practices.

Combining local knowledge and satellite images can be used to identify, and then address potential threats to a particular ecosystem more effectively.

# ANNEX 2. REGIONAL ECOSYSTEM AND BIODIVERSITY AGREEMENTS

This annex provides similar information to Annex 1, only for regional (as opposed to global) agreements.

### *A2.A. Agreement on the Conservation of African-Eurasian Migratory Waterbirds*

**History:** After the first Conference of Parties of the Convention on Migratory Species (the Bonn Convention), the Dutch Government began developing a draft Western Palearctic Waterfowl Agreement as part of its Western Palearctic Flyway conservation program. During the process of drafting and consultation, the name of the Agreement was changed to the African-Eurasian Waterbird Agreement (AEWA), emphasizing the importance of Africa for migratory birds. In June of 1994, the first meeting of Range States of AEWA was held in Nairobi, Kenya. In June of 1995, the final negotiations meeting was held in the Hague. The meeting adopted the agreement by consensus. The agreement went into force in 1999, when the required number of at least fourteen Range States, seven from Europe and seven from Africa, was achieved. At the first Session of the Meeting of the Parties, during November of 1999 in Cape Town, South Africa, the Parties decided to establish a Technical Committee and to create a permanent Secretariat.[31]

**Objective:** To maintain migratory waterbird species in a favorable conservation status or to restore them to such a status. These states should maintain general conservation measures and promulgate action plans and conservation guidelines, as recommended by Articles III and IV in the treaty.

**Implementation:** Increasing numbers of European states support the implementation of AEWA. Furthermore, in 2000 the Global Environment Facility (GEF) granted US $350,000 to draft a project brief of a full-size African-Eurasian Flyway GEF project of between US $8-12 million. The project aims to develop the transboundary strategic measures necessary to conserve the network of critical wetland areas on which migratory water birds depend throughout the Agreement area. The full-size project, if approved, will focus on: flyway and national protected area planning; capacity building; demonstration projects; cooperative research and monitoring and communications activities.[32]

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article III: General Conservation Measures
> (1) The Parties shall take measures to conserve migratory waterbirds, giving special attention to endangered species as well as to those with an unfavourable conservation status. (2) To this end, the Parties shall: …(c) identify sites and habitats for migratory waterbirds occurring within their territory and encourage the protection, management, rehabilitation and restoration of these sites… (d) coordinate their efforts to ensure that a network of suitable habitats is maintained or, where appropriate, re-established throughout the entire range of each migratory waterbird species concerned… (e) investigate problems that are posed

[31] http://www.unep-aewa.org/eng/backgr.htm (accessed June 2003)
[32] http://www.wcmc.org.uk/cms/aew_bkrd.htm (accessed June 2003)

> or are likely to be posed by human activities and endeavour to implement remedial measures, including habitat rehabilitation and restoration… (f) cooperate in emergency situations requiring international concerted action and in identifying the species of migratory waterbirds which are the most vulnerable to these situations… (h) initiate or support research into… the harmonization of research and monitoring methods and, where appropriate, the establishment of joint or cooperative research and monitoring programmes; (i) analyze their training requirements for, inter alia, migratory waterbird surveys, monitoring, ringing and wetland management to identify priority topics and areas for training and cooperate in the development and provision of appropriate training programmes; (j) develop and maintain programmes to raise awareness and understanding of migratory waterbird conservation issues in general and of the particular objectives and provisions of this Agreement; (k) exchange information and results from research, monitoring, conservation and education programmes; and (l) cooperate with a view to assisting each other to implement this Agreement, particularly in the areas of research and monitoring.

Remote sensing could be used to address many information requirements in this article, namely mapping waterbird habitats, including the critical habitats of endangered species, identifying and monitoring their maintenance, identifying emergency situations, and educating the public about the importance of maintaining migratory waterbird habitats through the use of remotely sensed image maps.

For example, the Ugandan study by Fuller *et al.* (1998) described in section IV.B. utilized field surveys of plants and animals in combination with satellite remote sensing of broad vegetation types to map biodiversity in the Sango Bay area off of Lake Victoria. A statistical classifier applied to satellite images identified 14 land-cover classes including water, swamp, dry grasslands, degraded woody vegetation, semi-natural forest classes and intensive land uses. These land cover types are of potential relevance to migratory bird species for feeding, breeding and nesting.

In areas where optical sensors suffer from cloud cover problems, radar remote sensors can be substituted because they can measure vegetation height and other multi-dimensional forest structural variables.[33] One study focused on radar mapping of vegetation structure and bird habitat (Imhoff and Sisk 1997). Airborne multi-frequency polarimetric radar showed that radar was successful in discerning structural differences relevant to bird habitat within similar community composition, and the abundance of individual bird species were observed to change significantly across both floristic and structural gradients. The authors concluded that “these results suggest that efforts to map bird diversity should focus on species-specific habitat relationships and that some measure of vegetation structure is needed to understand bird habitat.”

Satellite images can identify emergency situations that might affect migratory waterbirds, allowing ecosystem managers to assist species affected by a natural disaster. Finally, remote sensing could be used to increase public support for measures to protect waterbird habitat by showing, through remotely sensed image maps, the amount of habitat lost.

> <u>Article IV: Action Plan and Conservation Guidelines</u>
> An Action Plan is appended as Annex 3 to this Agreement. It specifies actions which the Parties shall undertake in relation to priority species and issues, under

[33] http://www.diggov.org/archive/library/pdf/bergen2.pdf (accessed on November 11, 2005)

> the following headings, consistent with the general conservation measures specified in Article III of this Agreement: (a) species conservation; (b) habitat conservation; (c) management of human activities; (d) research and monitoring; (e) education and information…
>
> Article V: Implementation and Financing
> (1) Each Party shall: (a) designate the Authority or Authorities to implement this Agreement which shall… monitor all activities that may have impact on the conservation status of those migratory waterbird species of which the Party is a Range State…

Monitoring techniques described under the sections addressing the Convention on Migratory Species and the Ramsar Convention are also applicable to these articles.

### *A2.B. ASEAN Agreement on the Conservation of Nature and Natural Resources*

**History:** ASEAN was founded to provide a framework for regional conservation cooperation. The main goals of the original ASEAN Declaration, as released in August of 1967, were: to promote the economic and social development of the region through cooperative programs; to safeguard the political and economic stability of the region against power rivalries; and to serve as a forum for the resolution of inter-regional differences.

**Objectives:** The goals of the agreement are to encourage Contracting Parties to take measures necessary to "maintain essential ecological processes and life-support systems, to preserve genetic diversity, and to ensure the sustainable utilization of harvested natural resources under their jurisdiction in accordance with scientific principles and with a view to attaining the goal of sustainable development."

**Implementation:** States participating in the convention must develop national conservation strategies, and coordinate these strategies within the framework of a conservation strategy for the region.

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article 3: Species and Genetic Diversity
> The Contracting Parties shall, wherever possible, maintain maximum genetic diversity by taking action aimed at ensuring the survival and promoting the conservation of all species under their jurisdiction and control. (2) To that end, they shall adopt appropriate measures to conserve animal and plant species… and more specifically: (a) conserve natural, terrestrial, freshwater and coastal or marine habitats; (b) ensure sustainable use of harvested species; (c) protect endangered species; (d) conserve endemic species; and (e) take all measures in their power to prevent the extinction of any species or sub-species. (3) In order to fulfill the aims of the preceding paragraph… Parties shall, in particular, endeavour to: (a) create and maintain protected areas; (b) regulate the taking of species and prohibit unselective taking methods; (c) regulate and, where necessary, prohibit the introduction of exotic species; (d) promote and establish gene banks and other documented collections of animal and plant genetic resources.

Remote sensing technology could be used to address many information requirements required by this article, namely by mapping species habitats, including the critical habitats of endangered species, identifying sites and monitoring their maintenance, and identifying emergency situations. For a discussion on how remote sensing could be used in these situations, see the example by Tamura and Higuchi (2000) described in the section on the Convention on Migratory Species.

> Article 4: Species and Sustainable Use
> The Contracting Parties shall… endeavour to: (1). Develop, adopt and implement management plans for those species, based on scientific studies and aiming at: (a) preventing decrease in the size of any harvested population to levels below those which ensure its stable recruitment and the stable recruitment of those species which are dependent upon, or related to them; (b) maintaining the ecological relationship between harvested, dependent and related populations of living resources of the ecosystem considered; (c) restoring depleted populations to at least the levels referred to in sub-paragraph (a) of this paragraph; (d) preventing changes or minimizing risk of changes in the ecosystem considered which are not reversible over a reasonable period of time…

Monitoring the growth rate of relevant ecosystems with remote sensing would ensure that they are being protected effectively by Contracting Parties. For examples of ecosystem monitoring with remote sensing, the section on the Ramsar treaty.

> Article 5: Species - Endangered and Endemic
> Appendix 1 to this Agreement shall list endangered species recognized by the Contracting Parties as of prime importance to the Region and deserving special attention. The Appendix shall be adopted by a meeting of the Contracting Parties. Accordingly, Contracting Parties shall, wherever possible: …(c) especially protect habitat of those species by ensuring that sufficient portions are included in protected areas.

Again, remote sensing can be used to map species habitats and monitor habitats.

> Article 6: Vegetation Cover and Forest Resources
> The Contracting Parties shall, in view of the role of vegetation and forest cover in the functioning of natural ecosystems, take all necessary measures to ensure the conservation of the vegetation cover and in particular of the forest cover on lands under their jurisdiction. (2) They shall… endeavour to: (a) control clearance of vegetation; prevent bush and forest fires; prevent overgrazing by, inter alia, limiting grazing activities to periods and intensities that will not prevent regeneration of the vegetation; (b) regulate mining operations with a view to minimizing disturbance of vegetation and to requiring the rehabilitation of vegetation after such operations; (c) set aside areas as forest reserves, inter alia, with a view to conserve the natural forest genetic resources; (d) in reforestation and afforestation planning avoid as far as possible monoculture causing ecological imbalance; (e) designate areas whose primary function shall be the maintenance of soil quality in the catchment considered and the regulation of the quantity and quality of the water delivered from it; (f) ensure, to the maximum extent possible, the conservation of their natural forests, particularly mangroves, with a view, inter alia, to maintaining maximum forest species diversity; (g) develop their forestry management plans on the basis of ecological principles

with a view to maintaining potential for optimum sustained yield and avoiding depletion of the resource capital.

Seto and Fragkias (2005) monitored mangrove conversion to shrimp aquaculture in Vietnam. More on that study is found on the section addressing the Ramsar Convention in Annex 1. See also the example of forest fire monitoring in Indonesia under Article 10 below.

<u>Article 7: Soil</u>
(1) The Contracting Parties shall, in view of the role of soil in the functioning of natural ecosystems, take measures, wherever possible towards soil conservation, improvement and rehabilitation; they shall, in particular, endeavour to take steps to prevent soil erosion and other forms of degradation, and promote measures which safeguard the processes of organic decomposition and thereby its continuing fertility. (2) To that effect, they shall, in particular, endeavour to: (a) establish land use policies aimed at avoiding losses of vegetation cover, substantial soil losses, and damages to the structure of the soil; (b) take all necessary measures to control erosion, especially as it may affect coastal or freshwater ecosystems, lead to siltation of downstream areas such as lakes or vulnerable ecosystems such as coral reefs, or damage critical habitats, in particular that of endangered or endemic species; (c) take appropriate measures to rehabilitate eroded or degraded soils including rehabilitation of soil affected by mineral exploitation.

States could monitor land use policies to successfully design policies that minimize soil erosion. See the section above addressing the Convention to Combat Desertification.

<u>Article 10: Environmental Degradation</u>
The Contracting Parties, with a view to maintaining the proper functioning of ecological processes, undertake, wherever possible, to prevent, reduce and control degradation of the natural environment and, to this end, shall endeavour to undertake, in addition to specific measures referred to in the following article: (a) to promote environmentally sound agricultural practice by, inter alia, controlling the application of pesticides, fertilizers and other chemical products for agricultural use, and by ensuring that agricultural development schemes, in particular for wetland drainage or forest clearance, pay due regard to the need to protect critical habitats as well as endangered and economically important species; (b) to promote pollution control and the development of environmentally sound industrial processes… (f) to pay… attention to the regulation of activities which may have adverse effects on processes which are ecologically essential or on areas which are particularly important or sensitive from an ecological point of view, such as the breeding and feeding grounds of harvested species.

Using remote sensing, agricultural expansion into wetlands or forested areas can be monitored to make sure that valuable lands are being protected. In addition, utilizing the technology to create habitat maps, would allow the monitoring of valuable habitats to ensure they are not degraded.

In Southeast Asia, fire is traditionally used by the shifting cultivators and small-scale farmers as a tool for clearing land. Fire has increasingly been used by large plantations to clear land and for conversion of forest into plantations and agricultural land. In time of drought, the fires may go out of control, resulting in severe damage to the forest and the surrounding region. The 1997/98 forest fire episode in Southeast Asia attracted international attention. The fires which occurred primarily in the Sumatra and Borneo islands and aggravated by the drought due to the El Nino Southern Oscillation phenomenon, resulted in increased aerosol loading (smoke-haze) over the region. Millions of hectares of land/forest were burnt. Extensive monitoring of the fires was undertaken using MODIS and SPOT images.[34]

> Article 11: Pollution
> The Contracting Parties, recognizing the adverse effect that polluting discharges…may have on natural processes and the functioning of natural ecosystems as well as on each of the individual ecosystem components, especially animal and plants species, shall endeavour to prevent, reduce and control such discharges, emissions or applications in particular by: … (c) establishing national environmental quality monitoring programmes, particular attention being paid to the effects of pollution on natural ecosystems, and co-operation in such programmes for the Region as a whole.

Water pollution levels can be monitored indirectly with remote sensing. Variables that measure eutrophication cannot be produced using in situ sampling, yet would be useful for assessing water quality. Yang *et al*. (2000) used water quality modeling and remote sensing to estimate algal growth rates, an important factor in eutrophication control. Algal growth and respiration rates were estimated using a water quality model and two-dimension spatially distributed water quality data derived from SPOT satellite imagery for the Te-Chi Reservoir in Taiwan. A nonlinear calibration model was developed to provide an alternative method to estimate biological parameters of algae besides in situ sampling and experiment. Overall, this model performed effectively in revealing the net algal growth rate, even though it did not result in a single value for both algal biological parameters.

> Article 12: Land Use Planning
> (1) The Contracting Parties shall, wherever possible in the implementation of their development planning, give particular attention to the national allocation of land usage. They shall endeavour to take the necessary measures to ensure the integration of natural resource conservation into the land use planning process and shall, in the preparation and implementation of specific land use plans at all levels, give as full consideration as possible to ecological factors as to economic and social ones. In order to achieve optimum sustainable land use, they undertake to base their land use plans as far as possible on the ecological capacity of the land. (2) The Contracting Parties shall, in carrying out the provisions of paragraph 1 above, particularly consider the importance of retaining the naturally high productivity of areas such as coastal zones and wetlands…

Land use maps could be created for certain regions to determine the extent to which current land use patterns are sustainable. These maps would monitor progress with respect to land use change making certain future land use patterns are more sustainable.

> Article 13: Protected Areas
> The Contracting Parties shall as appropriate establish… terrestrial, freshwater, coastal or marine protection areas for the purpose of safeguarding: the ecological and biological processes essential to the functioning of the ecosystems of the Region; representative samples of all types of ecosystem of the Region… They shall, in particular, take all measures possible… to preserve those areas which are

[34] http://www.crisp.nus.edu.sg/forest_fire/fire.html (accessed on November 10, 2005)

> of an exceptional character and are peculiar to their… region as well as those which constitute the critical habitats of endangered or rare species, of species that are endemic to a small area and of species that migrate between countries of Contracting Parties. (2) Protected areas established pursuant to this Agreement shall be regulated and managed in such a way as to further the objectives for the purpose of which they have been created… (4) Contracting Parties shall, in respect of any protected area established pursuant to this Agreement: (a) prepare a management plan and manage the area on the basis of this plan; (b) establish, wherever appropriate, terrestrial or aquatic buffer zones that shall be located around protected areas and which, in the case of marine areas, may include coastal land areas or watersheds of rivers flowing into the protected area… (5) Contracting Parties shall, in respect of any protected area established pursuant to this Agreement, endeavour to: …(b) prohibit the use or release of toxic substances or pollutants which could cause disturbance or damage to protected ecosystems or to the species they contain; (c) …control any activity exercised outside protected areas when such an activity is likely to cause disturbance or damage to the ecosystems or species that such protected areas purport to protect…

States can use remotely sensed data to identify species-rich areas worth protecting and then establish protected areas (see Section IV.D). An additional use of remote sensing would be monitoring for pollution near protected ecosystems.

> <u>Article 16: Education, Information and participation of the public, training.</u>
> (1) The Contracting Parties shall endeavour to promote adequate coverage of conservation and management of natural resources in education programmes at all levels. (2) They shall circulate as widely as possible information on the significance of conservation measures and their relationship with sustainable development objectives, and shall, as far as possible, organize participation of the public in the planning and implementation of conservation measures. (3) Contracting Parties shall endeavour to, individually or in co-operation with other Contracting Parties or appropriate international organizations, develop the programmes and facilities necessary to train adequate and sufficient scientific and technical personnel to fulfill the aims of this Agreement.

Remote sensing could be used to educate the public and to raise public support for measures to protect valuable ecosystems by showing, through image maps created from remotely sensed data, the amount of valuable land that has been lost to agriculture and urban expansion.

> <u>Article 18: Co-operative Activities</u>
> (1) The Contracting Parties shall co-operate together and with the competent international organizations, with a view to coordinating their activities in the field of conservation of nature and management of natural resources and assisting each other in fulfilling their obligations under this Agreement. (2) To that effect, they shall endeavour: (a) to collaborate in monitoring activities; (b) to the greatest extent possible, co-ordinate their research activities; (c) to use comparable or standardized research techniques and procedures with a view to obtaining comparable data; (d) to exchange appropriate scientific and technical data, information and experience, on a regular basis… (3) In applying the principles of co-operation and co-ordination set forth above, the Contracting Parties shall forward to the Secretariat: (a) information of assistance in the monitoring of the

> biological status of the natural living resources of the Region; (b) information, including reports and publications of a scientific, administrative or legal nature, and in particular information on: measures taken by the Parties in pursuance of the provisions of this Agreement the status of species included in Appendix 1: any other matter to which the Conference of the Parties may give special priority.

Remote sensing is particularly useful with respect to cooperative activities, because it can be easily interpreted and exchanged, as measures change against a universally understood base map. Collaborative monitoring has been going on in many regions, including in the Southeast Asian region through the UNEP-GRID center in Bangkok.

### *A2.C. Convention Concerning the Protection of Alps*

**History:** In 1989, the European Union and Environmental Ministers of seven European Alpine countries – Switzerland, France, Italy, Germany, Austria, Liechtenstein, and Slovenia – began meeting in order to produce a regional agreement for ensuring the protection and sustainable development of Alpine areas. Signed in 1991, the Convention entered into force on March 6, 1995. Four of the first eight implementing protocols have been signed, one has been approved for signature, with three still in a working status.[35]

**Objectives:** The Alpine Convention is intended to protect the Alps by applying the principles of prevention, payment by the polluter (the 'polluter pays' principle) and cooperation, after careful consideration of the interests of all the Alpine States, their Alpine regions and the European Economic Community, and through the prudent and sustained use of resources. In addition, interstate cooperation in the Alpine region will be intensified and extended both in terms of the territory and the number of subjects covered.

**Implementation:** The Alpine Conference is the highest body within the Convention. Made up of the Environmental Ministers of the contacting parties, it meets about once every two years in order to make executive decisions. The Standing Committee (also called the Senior Civil Servants Groups, or the SCSG) carries out the regular work of the Conference. Once the SCSG approves particular Protocols, and once they are revised following the national consultations, they return to the SCSG to finally be approved for signature by Environmental Ministers at the next Alpine Conference.

*Analysis of the Treaty Text with Respect to Remote Sensing*

> <u>Article 2: General Obligations</u>
> (1) In order to achieve the objective referred to in paragraph 1, the Contracting Parties shall take appropriate measures in particular in the following areas: …(2) regional planning: the objective is to ensure the economic and rational use of land and the sound, harmonious development of the whole region, particular emphasis being placed on natural hazards, the avoidance of under and overuse and the conservation or rehabilitation of natural habitats by means of a thorough clarification and evaluation of landuse requirements, foresighted integral planning and coordination of the measures taken; (3) prevention of air pollution: the objective is to drastically reduce the emission of pollutants and pollution problems in the Alpine region, together with inputs of harmful substances from

[35] http://www.mtnforum.org/resources/library/warss97a.htm

> outside the region… (4) soil conservation: the objective is to reduce quantitative and qualitative soil damage, in particular by applying agricultural and forestry methods which do not harm the soil, through minimum interference with soil and land, control of erosion and the restriction of soil sealing, (5) water management: the objective is to preserve or reestablish healthy water systems, in particular by keeping lakes and rivers free of pollution… (6) conservation of nature and the countryside: the objective is to protect… the countryside, so that ecosystems are able to function, animal and plants species, including their habitats, are preserved, nature's capacity for regeneration and sustained productivity is maintained, and the variety, uniqueness and beauty of nature and the countryside as a whole are preserved on a permanent basis; (7) mountain farming: the objective is… to maintain the management of land traditionally cultivated by man and to… promote a system of farming which suits local conditions and is environmentally compatible, taking into account the less favourable economic conditions; (8) mountain forests: the objective is to preserve, reinforce and restore the role of forests, in particular their protective role, by improving the resistance of forest ecosystems mainly by applying natural forestry techniques and preventing any utilization detrimental to forests, taking into account the less favourable economic conditions in the Alpine region…

Remote sensing applications for ecosystem management in mountain regions are essentially analogous to those for other regions, except for the vital importance of understanding topography and its relation to ecosystem functioning and services. Slope, aspect, and drainage all play significant roles in ecosystem functioning in alpine environments. Natural hazards such as landslides and avalanches can alter the landscape quickly. Therefore, integration of DEMs with remote sensing data is critical to a better understanding of both ecosystem functioning and natural hazards. A study by Polemio and Petrucci (2001) integrated several pieces of remotely sensed data to improve the knowledge of landslide hazard related to a seismic area in the southern Apennine of Italy. The analysis was validated using detailed topographical, geophysical, geotechnical and hydrogeological data. The presented methodology recommends the combined use of DEM, multi-temporal panchromatic visible aerial photographs and thermal infrared images, since the integration between these data and multidisciplinary monitoring data proved useful. The main hydrogeological pattern, the geological and geomorphological framework and the areas of latent instability can be clearly determined and much insight can be gained through the synoptic view in the relative short time needed to carry out the analysis.

Remote sensing can also be used to measure land quality and development.  A method based on data integration in a GIS of satellite images of different spatial resolution (Landsat TM and SPOT), Digital Elevation Models, geo-lithological maps, and some soil-landscape data, was developed and applied to a test area on a sector of the Italian northwestern Alps (Giannetti *et al.* 2001). After gathering, integrating, and processing the data, the resulting cartographic units were superimposed on a soil-landscape map created through stereoscopic interpretation of aerial photographs at the same scale (1:250,000). This comparison was used to verify the correctness of the satellite image processing steps and consistency with the map scale used. A larger scale application was also developed for grassland at 1:50,000 scale to demonstrate the practical use of remote sensing and GIS data in assisting mountainous land development.

> <u>Article 3: Research and systematic monitoring</u>
> In the areas specified in Article 2, the Contracting Parties shall agree to:

> Cooperate in the carrying out of research activities and scientific assessments; (2) develop joint or complementary systematic monitoring programmer; (3) harmonize research, monitoring and related data-acquisition activities.

The Convention implicitly refers to remote sensing here when it suggests systematic monitoring of sites and harmonization of monitoring and data acquisition activities.

> Article 4: Legal scientific, economic and technical cooperation
> The Contracting Parties shall facilitate and promote the exchange of legal, scientific, economic and technical information relevant to this Convention… (4) The Contracting Parties shall establish an appropriate program of public information on the results of research and observations as well as on measures taken... (5) The Contracting Parties' obligations under this Convention with regard to the provision of information shall be subject to compliance with national laws on confidentiality. Information designated confidential shall be treated as such.

Public support could be generated by showing, through image maps created from remotely sensed data, the amount of land that has been lost to development, or the impacts of development activities on land degradation through erosion and land slides.

### *A2.D. The Antarctic Treaty*

**History:** The International Council of Scientific Unions organized an 18-month study of Antarctica, from July 1, 1957 until December 31, 1958, which was known as the International Geophysical Year (IGY). Although the decision to participate heavily in the IGY was often politically motivated, the result was significant cooperation among scientists of different nations. Toward the end of the study period the USSR announced it would maintain the bases it established as the basis of a sector claim. The continued dispute between South American claimants and Great Britain, and the Soviet intent to maintain its bases made evident the need for an Antarctic accord. Consequently, other IGY parties sought a solution to territorial claims, ultimately resulting in the Antarctic Treaty of 1959. Argentina, Australia, Belgium, Chile, France, Great Britain, Japan, New Zealand, South Africa, the USSR and the United States of America signed the Antarctic Treaty on December 1, 1959. The Treaty applies to the area south of sixty degrees South latitude. The Treaty entered into force after ratification by all signatories on June 23, 1961.[36]

**Objectives:** The goals of the treaty were to avoid a confrontation among the claimant states on the issue of territorial claims and to preserve Antarctica for peaceful purposes. To ensure compliance, the Parties provided for the inspection of "[a]ll areas of Antarctica, including all stations, installations and equipment within those areas." Although the Treaty does not present an ultimate resolution to the issue of sovereign claims, the Parties were able to agree to hold their claims in abeyance during the period the Treaty is in force. While the Treaty does not contain any provisions for protection of the environment it did allow for the Parties to elaborate further agreements on such issues. The ability of the treaty to grow and provide for changing circumstances has been an important factor in its continued survival.

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[36] http://www.polarlaw.org/History.htm

**Implementation:** The only decision-making body in the Treaty system is a conference of parties, known as the Antarctic Treaty Consultative Meeting (ATCM), and only those states with consultative status have the right to vote. Parties receive consultative status when they demonstrate a special interest in Antarctica by conducting substantial scientific research activities. The Consultative Meetings take place each year in a different Party. In the 25 Consultative Meetings that have been held since 1961, more than 250 measures have now been adopted, the majority of which concerned protection of the Antarctic environment.[37]

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article III. In order to promote international cooperation in scientific investigation in Antarctica, as provided for in Article II of the present Treaty, the Contracting Parties agree that… (c) scientific observations and results from Antarctica shall be exchanged…

Given the harsh environment in Antarctica, remote sensing offers a useful tool for scientific observation. As has been observed in the context of other treaties, observations from remote sensing are particularly suitable for scientific exchange and communication.

> Article IX. Representatives of the Contracting Parties named in the preamble… shall meet at the City of Canberra within two months after the date of entry into force of the Treaty, and thereafter at suitable intervals and places, for the purpose of exchanging information, consulting together on matters of common interest pertaining to Antarctica, and formulating and considering, and recommending to their Governments, measures in furtherance of the principles and objectives of the Treaty, including measures regarding… (f) preservation and conservation of living resources in Antarctica.

Most remote sensing research on Antarctica is focused on geomorphology and glaciology, with extensive use of radar instruments. However, there are living resources in Antarctica, and to the extent that their habitats can be monitored from space, remote sensing may present a viable data source. A study in a comparable environment, the Aleutian Islands, looked at the ocean flow and bathymetry that define unique habitats influencing prey distribution and foraging behavior of top-level predators (Fadely *et al.* 2005). The researchers explored whether oceanographic features and bathymetry influenced the diving activity of 30 immature sea lions (ages 5-21 months) equipped with satellite-linked depth recorders in the eastern Aleutian Islands (EAI) during 2000-02. Sea surface temperature (SST) and chlorophyll a concentrations were obtained from remote sensing satellite imagery and associated with locations where sea lion diving was recorded. Diving activity varied with increases in SST and chlorophyll a concentrations, but also with sea lion age.

### *A2.E. Convention for Protection of Natural Resources and Environment of South Pacific Region (SPREP)*

**History:** The initial call for a Pacific island environmental organization first came in 1969 at a World Conservation Union Conference in Noumea, New Caledonia. Over the next decade, international support from UNEP and the Economic and Social Commission for Asian and the Pacific and other regional organizations grew, and in 1982, at the Conference on the Human

[37] http://www.auswaertiges-amt.de/www/en/aussenpolitik/vn/antarktis_html

Environment, which was held in Cook Islands, led to a formalized agreement that officially created SPREP.

**Objectives:** The objective of the Convention is to protect and manage the natural resources and environment of the South Pacific region. Contracting parties agree to take measures to reduce and control pollution in the Convention area, particularly from vessels, land based sources, exploration and exploitation of the sea-bed, airborne pollution, dumping, and the testing of nuclear devices. In addition, parties agree to prohibit storage of radioactive wastes in the Convention area, take steps necessary towards preserving rare flora and fauna, and cooperate in dealing with regional pollution emergencies.

**Implementation:** Although SPREP was established in 1982, it did not become an autonomous regional organization until 1995. In the last five years SPREP has expanded. Current projects include Waste Management Education and Awareness (with the European Union), and Atmospheric and Radiation Measurements in the Tropical Western Pacific (with the U.S. Department of Energy). In the future, SPREP plans to develop and implement programs such as Biodiversity and Natural Resource Conservation, Climate Change and Integrated Coastal Management, and Environmental Management, Planning and Institutional Strengthening.

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article 6: Pollution from vessels
> The Parties shall take all appropriate measures to prevent, reduce and control pollution in the Convention Area caused by discharges from vessels, and to ensure the effective application in the Convention Area of the generally accepted international rules and standards established through the competent international organisation or general diplomatic conference relating to the control of pollution from vessels.

Under the Bonn Agreement, monitoring procedures have been set up to track oil spills to their ships of origin. Because oil slicks change surface roughness of water bodies, radar instruments can easily detect them, as this difference registers as changes in backscatter on radar instruments (see section 3.4.2 – “oil spill response” – in de Sherbinin and Giri 2001).

> Article 7: Pollution from land-based sources
> The Parties shall take all appropriate measures to prevent, reduce and control pollution in the Convention Area caused by coastal disposal or by discharges emanating from rivers, estuaries, coastal establishments, outfall structures, or any other sources in their territory.

A study by Tripathi *et al.* (1998) investigated the feasibility of using the multiband ground truth radiometer (MGTR) for monitoring the pollution of the river Ganga by tanneries in Kanpur, India, by indirectly measuring Tannin concentration in the river. Although the conventional environmental engineering laboratory approach for determining Tannin concentration is time consuming and expensive, the results of this study show the potential for MGTR in monitoring land-based point source pollution.

> Article 13: Mining and coastal erosion
> The Parties shall take all appropriate measures to prevent, reduce and control environmental damage in the Convention Area, in particular coastal erosion

> caused by coastal engineering, mining activities, sand removal, land reclamation and dredging.

Remote sensing technology can be used to measure coastal erosion rates, in order to detect if human activities have increased coastal erosion rates. White and El Asmar (1999) used Landsat Thematic Mapper imagery in order to monitor large sections of the Nile Delta coastline. By comparing positions of the Delta in 1984, 1987, and 1990/1, they were able to map areas of rapid change.

> Article 14: Specially protected areas and protection of wild flora and fauna
> The Parties shall… take all appropriate measures to protect and preserve rare or fragile ecosystems and depleted, threatened or endangered flora and fauna as well as their habitat in the Convention Area. To this end, the Parties shall, as appropriate, establish protected areas, such as parks and reserves, and prohibit or regulate any activity likely to have adverse effects on the species, ecosystems or biological processes that such areas are designed to protect. The establishment of such areas shall not affect the rights of other Parties or third States under international law. In addition, the Parties shall exchange information concerning the administration and management of such areas.

The same remote sensing applications apply here as those described in other sections of this report related to protected areas design and management (Section IV.D).

### *A2.F. Convention on the Conservation of European Wildlife and Natural Habitats*

**History:** The Convention on the Conservation of European Wildlife and Natural Habitats, also known as the Bern Convention, was adopted in Bern, Switzerland on September 19, 1979 at the 3rd European Ministerial Conference on the Environment. On June 1, 1982 it came into force. The contracting parties to the convention at the first Standing Committee meeting included the European Economic Community and nine states. Today 45 European and African states are parties to the convention.

**Objectives:** To conserve wild fauna and flora and their natural habitats, especially those species and habitats whose conservation requires the cooperation of several States, and to promote such cooperation.

**Implementation:** Contracting parties agreed to take steps to promote national policies for conservation with particular attention to endangered and vulnerable species and endangered habitats. A Standing Committee was established and is responsible for monitoring the application of the Convention.

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article 6. Each Contracting Party shall take appropriate and necessary legislative and administrative measures to ensure the special protection of the wild fauna species specified in Appendix II. The following will in particular be prohibited for these species… (b) the deliberate damage to or destruction of breeding or resting sites.

> Article 10. The Contracting Parties undertake, in addition to the measures specified in Articles 4, 6, 7 and 8, to coordinate their efforts for the protection of the migratory species specified in Appendices II and III whose range extends into their territories.

Both of these articles have relevance for remote sensing, as demonstrated by the numerous applications for habitat protection mentioned earlier in this report, with special reference to those listed under the CMS and Ramsar sections of Annex 1.

### *A2.G. African Convention on the Conservation of Nature and Natural Resources*

**History:** The African Convention on the Conservation of Nature and Natural Resources was signed in Algiers, Algeria on September 15, 1968 and entered into force in 1969.

**Objectives:** For parties to adopt measures necessary to ensure conservation and development of soil, water, flora and fauna in accordance with scientific principles and with regard to the best interests of the people.

**Implementation:** A pioneering convention in conservation. Despite its comprehensive and innovative approach to conservation, it made the mistake of many other conventions in not establishing an administrative structure to oversee its supervision (Freestone, *undated*). As a result, it has largely been superseded by global treaties such as CITES and the CBD. Nevertheless, it has had an important impact on national-level legislation. For example, Tanzania ratified the African Convention in 1974, the year that it promulgated its own Wildlife Conservation Act. Most of the provisions of the Convention that seek to regulate and control hunting have been re-echoed in the Wildlife Conservation Act.[38]

*Analysis of the Treaty Text with Respect to Remote Sensing*

> Article IV: Soil. The Contracting States shall take effective measures for conservation and improvement of the soil and shall in particular combat erosion and misuse of the soil. To this end: (a) they shall establish land-use plans based on scientific investigations (ecological, pedological, economic, and sociological) and, in particular, classification of land-use capability; (b) they shall, when implementing agricultural practices and agrarian reforms, (i) improve soil conservation and introduce improved farming methods, which ensure long-term productivity of the land, (ii) control erosion caused by various forms of land-use which may lead to loss of vegetation cover.

Applications of remote sensing for soil quality assessment are still largely experimental, but they are showing early promise. Research in Kenya identified new ways of combining rapid soil analysis using visible-near-infrared spectroscopy (VIS-NIR) and remote sensing imagery to provide a framework for precision mapping of soil physical condition indicators in tropical watersheds (Thine 2004). VIS-NIR soil spectral reflectance, obtained from hand-held instruments, is relatively easy to sample over large areas and was calibrated with hydraulic properties that are sensitive to soil physical degradation. Partial least squares calibration of soil spectral reflectance with hydraulic properties showed satisfactory correlation ($r^2 > 0.50$) that

[38] http://www.leat.or.tz/publications/regulating.hunting/2.2.african.convention.php (accessed November 11, 2005)

enabled the spectra to be used as surrogate variable in the characterization of physical degradation. A soil physical condition index was also developed. Using this index, soil physical condition classes which distinctly displayed different hydraulic properties, could reliably be mapped using Landsat imagery.

> Article VI: Flora. (1) The Contracting States shall take all necessary measures for the protection of flora and to ensure its best utilization and development. To this end… States shall: (a) Adopt scientifically-based… management plans of forests and rangeland, taking into account the social and economic needs of the States concerned, the importance of the vegetation cover for the maintenance of the water balance of an area, the productivity of soils and the habitat requirements of the fauna; (b) Observe section (a) above by paying particular attention to controlling bush fires, forest exploitation, land clearing for cultivation, and over-grazing by… (c) Set aside areas for forest reserves and carry out afforestation programmes where necessary; (d) Limitation of forest grazing to season and intensities that will not prevent forest regeneration; and (e) Establish botanical gardens to perpetuate plant species of particular interest. (2) The Contracting States also shall undertake the conservation of plant species… which are threatened and/or of special scientific or aesthetic value by ensuring that they are included in conservation areas.

> Article VII: Faunal Resources. The Contracting States shall ensure conservation, wise use and development of faunal resources and their environment, within the framework of land-use planning and of economic and social development. Management shall be carried out in accordance with plans based on scientific principles and to this end the Contracting States shall: (a) Manage wildlife populations inside designated areas according to the objectives of such areas and also manage exploitable wildlife populations outside such areas for an optimum sustained yield, compatible with and complementary to other land uses; and (b) Manage aquatic environments… with a view to minimise deleterious effects of any water and land use practice which might adversely affect aquatic habitats.

Remote sensing can be used to map and monitor flora and fauna habitat, among other things. See earlier examples in Chapter IV and Annex 1. Remote sensing has been used effectively to monitor elephant habitat in Africa (see Section III.B.3), and to better understand and anticipate human-elephant conflicts. Foley (2002) sought to understand elephant distribution and migration patterns, developing one habitat suitability model based purely on remotely sensed factors, and another that used a logistic regression incorporating both remotely sensed factors and ecological parameters. The logistic regression model resulted in a much smaller area classified as suitable for elephants. There was a discrepancy between the amount of land actually used by the elephants (from radio collar data) and that which was modeled as suitable. The NDVI values inside and outside the park were significantly different, with the values being consistently higher in the national park. Foley reports that it is likely that specific mineral content of the soil and vegetation, particularly sodium and potassium, is more important to animal movement than the greenness or abundance of forage available. Human presence/absence also affected elephant distribution.

> Article VIII: Protected Species. The Contracting States recognize that it is important and urgent to accord a special protection to those animal and plant species that are threatened with extinction or which may become so, and to the habitat necessary to their survival. Where such a species is represented only in the territory of one Contracting State, that State has a particular responsibility for its protection. These species which are, or may be listed, according to the degree of protection that shall be given to them are placed in Class A or B of the Annex to this Convention, and shall be protected by Contracting States as follows: (i) species in Class A shall be totally protected throughout the entire

> territory of the Contracting States; the hunting, killing, capture or collection of specimens shall be permitted only on the authorization in each case of the highest competent authority and only if required in the national interest or for scientific purposes; and (ii) species in Class B shall be totally protected, but may be hunted, killed, captured or collected under special authorization granted by the competent authority.
>
> Article X: Conservation Areas. The Contracting States shall maintain and extend where appropriate… the Conservation areas existing at the time of entry into force of the present Convention and, preferably within the framework of land-use planning programmes, assess the necessity of establishing additional conservation areas in order to: (i) protect those ecosystems which are most representative of and… those which are… peculiar to their territories, (ii) ensure conservation of all species and more particularly of those listed or which may be listed in the annex to this Convention; (2) The Contracting States shall establish, where necessary, around the borders of conservation areas, zones within which the competent authorities shall control activities detrimental to the protected natural resources.

Remote sensing can be used to design and monitor protected areas; see Section IV.D and examples addressing the CBD.

### *A2.H. Meso-American Biological Corridor*

**History:** The Central American Commission for Sustainable Development (CCAD) originally proposed the idea of a corridor in 1995 as a coordinated regional program to prevent biodiversity loss. The Global Environmental Facility approved its establishment with funding from the United Nations Development Program and the World Bank. In 1997, at a Central American Summit, the presidents of the countries committed to the MBC.

**Objectives:** The MBC seeks to protect seas, rivers, and vast tracts of land as a corridor for wildlife migration. The corridor is also intended to promote sustainable economic development.

**Implementation:** Although financial and political commitments have been obtained from donors and governments, still lacking are public awareness, local support, and broad public and private agency involvement. One attempt to combat this problem is the Project to Consolidate the MBC, which is a specific incentive to facilitate the implementation of the regional strategy of the MBC.

> Vision of the MBC. … The key objective is to conserve watersheds and coastal zones, restore degraded landscapes, and protect a series of priority areas. This will create ecological corridors along which animals can roam undeterred, facilitating genetic exchange and promoting species survival…

Through a joint NASA-CCAD project, remote sensing technology is helping address the goals of the MBC, from learning about existing Mesoamerican land use patterns to using information on land cover in order to assess to the seriousness of biodiversity conservation problems.[39]

[39] http://weather.msfc.nasa.gov/corredor/corredor.html (accessed July 2005).

# ANNEX 3. REMOTE SENSING AND RELATED RESOURCES

This annex provides a list of online resources relevant to the application of remote sensing to biodiversity conservation, ecosystem management treaties, and transboundary conservation.

**Center for Applied Biodiversity Science (CABS) GIS Lab**
**Sponsor:** Conservation International
**Description:** CABS recognizes that biodiversity information is a key requirement for the success of any conservation initiative. Field research projects both require and produce enormous amounts of information that needs to be managed, analyzed, and presented in cost-effective ways. Over 80 percent of all conservation-related data have associated geographic attributes, and are most usefully analyzed in a geographic information system.
**Website:** http://www.biodiversityscience.org/xp/CABS/research/gis/gis.xml

**Global Forest Watch**
**Sponsor:** World Resources Institute
**Description:** Global Forest Watch monitors the world's remaining forest frontier areas using remote sensing and GIS to detect illegal cutting. The website has a data download page for GIS data and remote sensing imagery.
**Website:** http://www.globalforestwatch.org/

**Global Transboundary Protected Areas Network**
**Sponsor:** IUCN
**Description:** This web resource provides documents, case studies, and other information on the subject of transboundary protected areas.
**Website:** http://www.tbpa.net

**Protected Areas Archive (PAA)**
**Sponsor:** NASA Jet Propulsion Laboratory
**Description:** The PAA provides pre-formatted imagery from Modis, Landsat and Aster to selected protected areas around the world. It also integrates protected areas boundaries from the World Database of Protected Areas. It is an easy-to-use tool for protected area managers, and has the capability to upload new imagery and shape files.
**Website:** http://asterweb.jpl.nasa.gov/paa.asp

**Remote Sensing Resource Pages**
**Sponsor:** the Remote Sensing and Geographical Information Systems (RS/GIS) Facility, Center for Biodiversity Conservation, American Museum of Natural History
**Description:** This website provides a wealth of information on conservation-related remote sensing applications. It provides users with pointers to the major archives of remote sensing data together with useful tips on how to obtain imagery at the lowest possible cost. It also provides a description of available remote sensing tools, from image processors such as Adobe's Photoshop to fully fledged analytical tools like ERDAS Imagine and ENVI. Of particular interest to budget conscious or relatively new remote sensing users are the shareware software packages available for download from the internet.
**Website:** http://cbc.rs-gis.amnh.org/

**Socioeconomic Data and Applications Center (SEDAC)**
**Sponsor:** NASA
**Description:** SEDAC is a Distributed Active Archive Center funded by the NASA that harnesses state-of-the-art information technologies to help bridge the gap between the earth and social sciences. SEDAC's internet site provides on-line data sets that may be of use to researchers wishing to combine remote sensing data with ancillary socioeconomic data such as population or income in a GIS.
**Website:** http://sedac.ciesin.columbia.edu/

**Tropical Rainforest Information Center**
**Sponsor:** Michigan State University and NASA
**Description:** The Tropical Rain Forest Information Center is a NASA Earth Science Information Partner (ESIP). Its mission is to provide NASA data, products and information services to the science, resource management, and policy and education communities. TRFIC provides Landsat and other high resolution satellite remote sensing data as well as digital deforestation maps and databases to a range of users through web-based geographic information systems. Its Landsat data inventory provides Landsat imagery for as low as US$50 per scene.
**Website:** http://www.bsrsi.msu.edu/trfic/

# ANNEX 4. SATELLITES AND SENSORS

The following table lists the most known and used satellites and their sensors, with specifications about spectral, spatial, and temporal resolutions (see Chapter II for details on these three types of resolution), what they can detect, and applications for which they can be used.

| Satellite | Sensor | Spectral Resolution (Wavelength in µm) | Spatial Resolution | Temporal Resolution | What Can Be Detected? | |
|---|---|---|---|---|---|---|
| | | | | | Spatial | Temporal |
| **LANDSAT 4, 5**<br><br>URL:<br>*http://geo.arc.nasa.gov/sge/landsat/landsat.html* | **MSS**<br>(Multispectral scanner system) | **1**: 0.5-0.6 (G)<br>**2**: 0.6-0.7 (R)<br>**3**: 0.7-0.8 (VNIR)<br>**4**: 0.8-1.1 (NIR) | 80 m;<br>185 Km swath width | 16 days | Mapping coastal features in sediment-laden water<br>Mapping roads and urban areas<br>Vegetation studies and mapping land/water boundaries | Deforestation<br>Urban and suburban development |
| | **TM**<br>Thematic Mapper | **1**: 0.45-0.515 (B)<br>**2**: 0.52-0.60 (G)<br>**3**: 0.63-0.69 (R)<br>**4**: 0.75-0.90 (NIR)<br>**5**: 1.55-1.75 (Mid-IR)<br>**6**: 10.40-12.5 (thermal)<br>**7**: 2.09-2.35 (Mid-IR) | 30 m (visible, near and mid-IR);<br>120 m (thermal IR);<br>185 Km swath width | 16 days | Soil/vegetation differentiation & coastal water mapping<br>Vegetation mapping<br>Plant species differentiation<br>Biomass survey<br>Snow/cloud differentiation<br>Thermal mapping<br>Geological mapping | Changes in heat islands<br>Vegetation/land use patterns |
| **LANDSAT 7**<br>(1, 2, 3, 6 are inactive)<br><br>URL:<br>*http://landsat7.usgs.gov/* | **ETM +**<br>(Enhanced Thematic Mapper) | **1**: 0.45-0.515 (B)<br>**2**: 0.52-0.60 (G)<br>**3**: 0.63-0.69 (R)<br>**4**: 0.75-0.90 (NIR)<br>**5**: 1.55-1.75 (Mid-IR)<br>**6**: 10.40-12.5 (thermal)<br>**7**: 2.09-2.35 (Mid-IR)<br>**8**: 0.52-0.90 (pan) | 30 m (visible, near and mid-IR),<br>15 m (panchromatic), 60 m (Thermal Infrared);<br>185 Km swath width | 16 days | Major Thoroughfares<br>Large Buildings<br>Forest Stands<br>Agricultural Plots<br>Coastline Advance/Retreat<br>Rugged Topography<br>Sea Ice Coverage | Changes in human infrastructure<br>Development patterns<br>Migration patterns<br>Agricultural variations<br>Urban/Rural interchange |

*Note: Spectral resolutions are coded as follows: B = Blue, G = Green, R = Red, VNIR = Visible Near Infrared, NIR = Near Infrared, SWIR = Shortwave Infrared, mid-IR = Middle Infrared, pan = Panchromatic.*

<table>
<tr><th rowspan="2">Satellite</th><th rowspan="2">Sensor</th><th rowspan="2">Spectral Resolution (Wavelength in µm)</th><th rowspan="2">Spatial Resolution</th><th rowspan="2">Temporal Resolution</th><th colspan="2">What Can Be Detected?</th></tr>
<tr><th>Spatial</th><th>Temporal</th></tr>
<tr><td rowspan="2">SPOT 1, 2, and 4 (3 is inactive)<br>Launched by France from 1986-1998<br><br>SPOT 5<br>Launched in may 2002<br><br>URL:<br>www.spot.com/</td><td>Two HRV-IR (High Resolution Visible, Infrared) push-broom sensors.<br><br>Provides coverage between 87 degrees north and 87 degrees south</td><td>1: 0.50-0.59 (G)<br>2: 0.61-0.68 (R)<br>3: 0.79-0.89 (NIR)<br>4: 1.58-1.73 (SWIR) – added on SPOT 4<br>Pan: 0.51-0.73</td><td>20 m (Visible, Near Infrared), 10 m (panchromatic);<br>60 Km swath width</td><td>26 days</td><td rowspan="2">Agriculture (Resource mapping, production management, crop classification)<br>Land Use (Urban and suburban land use, land mapping, energy, human infrastructure)<br>Oceanography (water quality management)<br>Water resources (Surface water, soil moisture and evapotranspiration, lakes and rivers studies, wetlands and habitat mapping, resource assessment)<br>Geological applications (mapping, economic geology, engineering geology, hazards and land morphology. oil and gas exploration)<br>Engineering applications (terrain analysis, site investigation, water resources engineering, transport studies.</td><td rowspan="2">Deforestation<br>Suburban/Urban land use changes<br>Residential Development<br>Coastal Pollution<br>Water resource pollution monitoring<br>Snow and Ice mapping<br>Harvest forecasting<br>Conservation monitoring<br>Hazard prediction<br>Landslide hazards<br>Forest damage assessment</td></tr>
<tr><td>High Resolution Geometry (HRG), the high spatial resolution version of SPOT 4 HRV-IR</td><td>1: 0.50-0.59 (G)<br>2: 0.61-0.68 (R)<br>3: 0.79-0.89 (NIR)<br>4: 1.58-1.73 (SWIR) – added on SPOT 4<br>Pan: 0.51-0.73</td><td>10 m (Visible),<br>20 m (Near Infrared),<br>5 m (panchromatic);<br>60 Km swath width</td><td>26 days</td></tr>
</table>

| Satellite | Sensor | Spectral Resolution (Wavelength in µm) | Spatial Resolution | Temporal Resolution | What Can Be Detected? Spatial | Temporal |
|---|---|---|---|---|---|---|
| | **VEGETA-TION** instrument (on SPOT 4). | 1: 0.43-0.47 (B)<br>2: 0.61-0.68 (R)<br>3: 0.78-0.89 (NIR)<br>4: 1.58-1.75 (SWIR) | 1 Km; 2200 Km swath width | Daily | Forest monitoring (inventory, forest management) and vegetation cover study (especially the VEGETATION sensor) | |
| **IKONOS 1, 2** Launched in 1999 by the United States (IKONOS 2 failed)<br><br>URL: http://www.tbs-satellite.com/tse/online/sat_ikonos_2.html | **MMS** (Multispectral) and PAN (Panchromatic) | 1: 0.45-0.53 (B)<br>2: 0.52-0.61 (G)<br>3: 0.64-0.72 (R)<br>4: 0.76-0.88 (VNIR)<br>Pan: 0.45 – 0.90 | 4 m (visible), 1 m (panchromatic); 11 Km swath width | 26 days (680 km sun-synchronous orbit) | Roads, vehicles, buildings, infrastructure (panchromatic)<br><br>Land use, agricultural uses, vegetation (color imager) | Changes in human infrastructure Development patterns Migration patterns Agricultural variations Urban/Rural interchange |
| **Quickbird** Launched in October 2001<br><br>URL: http://www.digitalglobe.com | **MS** (Multispectral) and PAN (Panchromatic) | 1: 0.45-0.52 (B)<br>2: 0.52-0.60 (G)<br>3: 0.63-0.69 (R)<br>4: 0.76-0.99 (NIR)<br>Pan: 0.45-0.90 | 2.44 m (Multispectral); 61 cm (panchromatic); 16.5 Km swath width | 1 to 3.5 days depending on latitude at 70-centimeter resolution | Roads, vehicles, buildings, infrastructure (panchromatic)<br><br>Land use, agricultural uses, vegetation (color imager) | Changes in human infrastructure Development patterns Migration patterns Agricultural variations Urban/Rural interchange |
| **NOAA - 7** Launched in 1981 and deactivated 1986 due to an power failure<br><br>URL: http://podaac.jpl.nasa.gov/sst/ | **AVHRR** (Advanced Very High Resolution Radiometer) | 1: 0.58-0.68 (G and R)<br>2: 0.72-1.10 (NIR)<br>3: 3.53-3.93 (Mid-IR)<br>4: 10.3-11.3 (Thermal IR)<br>5: 11.5-12.5 (Thermal IR) | 4.4 Km (Global Area Coverage), 1.1 Km (Local Area Coverage); 2800 Km swath width | 2 times per day; 8-day and monthly averaged data available | Day and night cloud top and sea surface temperatures Ice and snow conditions | Changes in climate and global land and sea temperatures Changes in snow and ice coverages |

| Satellite | Sensor | Spectral Resolution (Wavelength in µm) | Spatial Resolution | Temporal Resolution | What Can Be Detected? | |
|---|---|---|---|---|---|---|
| | | | | | Spatial | Temporal |
| **AVIRIS** Airborne Visible Infrared Spectrometer (instrument on board of planes) URL: http://makalu.jpl.nasa.gov/aviris.html | **Hyperspectral airborne sensor** Uses a scanning mirror in a "wisk broom" manner | Contains 224 different detectors each with a wavelength sensitive range of 10 nm, allowing it to cover the entire range between 0.4 and 25 µm. | 20 m (high altitude), 4 m (low altitude); 11 Km swath width | Only scheduled flights | Ecology (chlorophyll, leaf water, lignin, cellulose, pigments, structure, non-photosynthetic constituents) Geology (mineralogy, soil type) Cloud and Atmospheric studies (water vapor, clouds properties, aerosols, absorbing gases) Oceanography/Coastal and Inland Waters (chlorophyll, dissolved organics, sediments, bottom composition, bathymetry) Snow and Ice Hydrology (grainsize, impurities) Biomass burning (smoke, combustion products) Environmental Hazards Commercial | Snow and Ice Hydrology (melting, snow cover fraction) Commercial (agricultural correction) Ecology (changes in vegetation and community maps) Oceanography (changes in plankton coverage and chlorophyll) Forest Fires |
| **ERS2** (Active) | **AMI** (Active Microwave Instrumentation) with SAR-Image Mode, SAR-Wave Mode, Scatterometer Mode and Radar Altimeter | 5.3 GHz (C-Band) 13.5 GHz for the Radar Altimeter | 30 m (SAR) 50 Km (Scatterometer); 80-100 Km swath width (SAR-Image mode); 5 Km swath width (SAR-Wave mode), 500 Km swath width (Scatterometer mode) | 3 day, 35 day or 168 day cycles | All-weather instrument Ocean wave height/lengths, wind speed/direction, ice parameters, sea surface & cloud top temperatures, cloud cover and atmospheric water vapor. | Alterations and observations in ocean, land, ice, atmosphere, and climate Flood activity Changes in ocean activity, coastal regions and ice caps |

| Satellite | Sensor | Spectral Resolution (Wavelength in µm) | Spatial Resolution | Temporal Resolution | What Can Be Detected? | |
|---|---|---|---|---|---|---|
| | | | | | Spatial | Temporal |
| **ERS2** (Cont'd) | **ATSR-M** (Along Track Scanning Radiometer with Microwave Sounder) | 1.6, 3.7, 11, 12 (IR), 23.5 and 36.5 GHZ (Microwave) | 1 Km (IR), 22 Km (Microwave) ; 500 Km swath width | 3 day, 35 day or 168 day cycles | All-weather instrument Ocean wave height/lengths, wind speed/direction, ice parameters, sea surface & cloud top temperatures, cloud cover and atmospheric water vapor. | Alterations and observations in ocean, land, ice, atmosphere, and climate Flood activity Changes in ocean activity, coastal regions and ice caps |
| | **GOME** (Global Ozone Monitoring Experiment). Sensor is a double spectrometer | 1: 0.24-0.295<br>2: 0.29-0.405<br>3: 0.40-0.605<br>4: 0.59-0.79 | 40 x 2Km 40 x 320 Km; 960 Km swath width | | | |
| | **AATSR** (Advanced Along Track Scanning Radiometer) | 0.65, 0.85, 1.27, 1.6 | 0.5 Km; 500 KM swath width | | | |
| **SEASTAR**<br><br>URL: [http://seawifs.gsfc.nasa.gov/SEAWIFS.html](http://seawifs.gsfc.nasa.gov/SEAWIFS.html) | **SeaWiFS** (Sea-viewing Wide Field Sensor) | 1: 0.402-0.422<br>2: 0.433-0.453<br>3: 0.480-0.5<br>4: 0.5-0.520<br>5: 0.545-0.565<br>6: 0.66-0.68<br>7: 0.745-0.785<br>8: 0.845-0.885 | 1.1 Km (local area coverage) 4.5 Km (global area coverage); 285 Km swath width | 1 day | Ocean color and chlorophyll<br>Subsurface scattering<br>Atmospheric correction<br>Atmospheric correction<br>Sea-surface temperature | Changes in phytoplankton<br>Designed to provide global coverage of the oceans on a regular basis |
| **TERRA** Launched December 1999<br><br>URL: [http://terra.nasa.gov/About/](http://terra.nasa.gov/About/) | **ASTER** (Advanced Spaceborne Thermal Emission and Reflection Radiometer) | 14 bands, with wavelengths ranging from 0.52 to 11.65 | 15 m (VNIR), 30 m (SWIR), 90 m (TIR); 60 Km swath width | 4-16 days By request | Major Thoroughfares<br>Large Buildings<br>Forest Stands<br>Agricultural Plots<br>Coastline Advance/Retreat<br>Rugged Topography<br>Sea Ice Coverage | Infrastructure Changes<br>Residential Developments<br>Deforestation /Reforestation<br>Harvest<br>Flood Area<br>Landslides & Mass Movements |

| Satellite | Sensor | Spectral Resolution (Wavelength in µm) | Spatial Resolution | Temporal Resolution | What Can Be Detected? | |
|---|---|---|---|---|---|---|
| | | | | | Spatial | Temporal |
| | **MODIS** (Moderate Resolution Imaging Spectro-Radiometer) | 36 bands, with wavelengths ranging from 0.405 to 14.38 | 250 m (bands 1-2), 500 m (bands 3-7), 1000 m (bands 8-36); 2330 x 10 Km swath width | 1 to 2 days | Ideal for large scale changes in the biosphere, measures photosynthetic activity of land and marine plants<br>Surface temperature measurements,<br>Deforestation Forests, Open Canopy Vegetation, Large Scale Agriculture<br>Water Clarity, Atmospheric Aerosols, Smoke Plumes, Snow Cover, Ocean Temperature | Forest Fires<br>Regional Harvest/ Cycles<br>Plankton Blooms<br>Sediment Plumes<br>Maps extent of snow and ice brought by winter storms and frigid conditions |
| | **MISR** (Multi-angle Imaging Spectro-Radiometer) | 4 bands, with wavelengths ranging from 0.44 to 0.86 | 275 m; 360 Km swath width | 9 days | The amount of sunlight scattered in the atmosphere under natural conditions,<br>Atmospheric aerosol particles (formed by both natural and human activities)<br>Cloud Cover/Type, Vegetation Type | Smoke Plumes<br>Regional Air Quality<br>Climate<br>Regional Forest Canopy Structure |
| | **CERES** (Clouds and Earth's Radiant Energy System) | Shortwave: 0.3-5<br>Longwave: 8-12<br>Total: 0.3->200 | 20 km | Daily | Cloud/radiation flux measurements for models of oceanic and atmospheric energetics<br>The cross track mode continues measurements of Earth Radiation Budget Experiment and Tropical Rainfall Measuring Mission | Contributes to wider range weather forecasting |
| | **MOPITT** (Measure-ment of Pollution in the Tropo-sphere) | 2.3 ($CH_4$)<br>2.4 and 4.7 (CO) | 22 Km horizontally and 3 Km vertically; 640 Km swath width | 3 – 4 days | Measurements of pollution in the troposphere<br>Used to determine the amount of Carbon dioxide and methane in the atmosphere | |

| Satellite | Sensor | Spectral Resolution (Wavelength in µm) | Spatial Resolution | Temporal Resolution | What Can Be Detected? Spatial | Temporal |
|---|---|---|---|---|---|---|
| **AQUA** Launched May 2002<br><br>URL: [http://aqua.gsfc.nasa.gov/](http://aqua.gsfc.nasa.gov/) | **MODIS** (Moderate Resolution Imaging Spectro-Radiometer) | 36 bands, with wavelengths ranging from 0.405 to 14.38 | 250 m (bands 1-2), 500 m (bands 3-7), 1000 m (bands 8-36); 2330 x 10 Km swath width | 1 to 2 days | Ideal for large scale changes in the biosphere, measures photosynthetic activity of land and marine plants<br>Surface temperature measurements, Deforestation Forests, Open Canopy Vegetation, Large Scale Agriculture Water Clarity, Atmospheric Aerosols, Smoke Plumes, Snow Cover, Ocean Temperature | Forest Fires Regional Harvest/ Cycles Plankton Blooms Sediment Plumes Maps extent of snow and ice brought by winter storms and frigid conditions |
| | **CERES** (Clouds and Earth's Radiant Energy System) | Shortwave: 0.3-5<br>Longwave: 8-12<br>Total: 0.3->200 | 20 km | Daily | Cloud/radiation flux measurements for models of oceanic and atmospheric energetics<br>The cross track mode continues measurements of Earth Radiation Budget Experiment and Tropical Rainfall Measuring Mission | Contributes to wider range weather forecasting |
| | **AMSR/E** (Advanced Microwave Scanning Radiometer) | 12 channels and 6 frequencies ranging from 6.9 to 89.0 GHz (center frequency at 6.925, 10.65, 18.7, 23.8, 36.5 and 89.0 GHz) | Ranging from 56 km (at 6.925 GHz) to 5.4 km (at 89.0 GHz); 1445 km swath width | Daily | Cloud properties; radiative energy flux; precipitation; land surface wetness; sea ice; snow cover; sea surface temperature; sea surface wind fields | Contributes to weather forecasting and Climate Models |
| | **AIRS** (Atmospheric Infrared Sounder) | 2,300 spectral channels in the range of 0.4 to 1.0 and 3.4 to 15.4 | 13.5 km (IR) and 2.3 km (VIS/NIR); 1650 km swath width | Daily | Measures atmospheric temperature and humidity; land and sea surface temperatures; cloud properties; radiative energy flux | |

| Satellite | Sensor | Spectral Resolution (Wavelength in µm) | Spatial Resolution | Temporal Resolution | What Can Be Detected? | |
|---|---|---|---|---|---|---|
| | | | | | Spatial | Temporal |
| | **AMSU** (Advanced Microwave Sounding Unit) Consists of two sensors: AMSU-A1 ans AMSU-A2 | 15 discrete channels in the range of 50 to 89 GHz | 40 km; 1650 km swath width | Daily | Measures atmospheric temperature and humidity | |
| | **HSB** (Humidity Sounder for Brazil) | 4 channels: 1 at 150 GHz, 3 at 183 GHz | 13.5 km; 1650 km swath width | Daily | Aimed at obtaining humidity profiles throughout the atmosphere | |

*Source: de Sherbinin, A., D. Balk, K. Yager, M. Jaiteh, F. Pozzi, C. Giri, and A. Wannebo. 2002. "Social Science Applications of Remote Sensing," A CIESIN Thematic Guide, Palisades, NY: Center for International Earth Science Information Network of Columbia University. Available on-line at http://sedac.ciesin.columbia.edu/tg/guide_main.jsp*

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**The Project on Remote Sensing Technologies for Ecosystem Management Treaties**

PROBIDES

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