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Feasibility of Using Remotely Sensed Data to Aid in Long-term Monitoring of Biodiversity

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1. Introduction

The United States Agency for International Development (USAID) invests about $200 million each year in conservation and protection efforts in strategic ecosystems around the globe. With offices in over 50 countries and projects ranging from support of forest conservation in Africa to monitoring of coastal environments in the Philippines, USAID focuses on conserving biodiversity while advancing development, particularly for communities reliant on natural resources for their livelihoods

The Forestry and Biodiversity (FAB) Office is developing new methods for evaluating and monitoring the effectiveness of the programmatic investments that have been made over the past two decades, as well as current and future investments. Evaluation of the impact of conservation efforts is time consuming, expensive and often dependent on local knowledge – challenges that are compounded when working in a developing country context. Access to areas that are critical to evaluate can also be limited due to geographic remoteness. Furthermore, conservation funding is often inadequate to effectively address the myriad threats to biodiversity and program staff may be reluctant to allocate limited funds to evaluation and monitoring. As a result of these various factors, the effectiveness of common approaches to biodiversity conservation and development such as livelihood programs and capacity building remain poorly understood in many settings (Brooks, Wright and Sheil 2009).

Observing areas that are a priority for FAB programming with remote sensing can provide important information on biodiversity patterns and ecosystem changes. Remote sensing provides information that is equally valid regardless of political boundaries or geographic locations. Additionally, remote sensing can be used to observe ecosystems in areas that are otherwise inaccessible or isolated.

This report will first briefly define "remote sensing" and "biodiversity" for the purposes at hand, and then discuss how remote sensing can be applied to biodiversity monitoring. Its objectives are to show how the increasing length of record and diversity of biophysical measurements from remote sensing can be used to inform the community that is concerned with the monitoring and conservation of biodiversity. The main focus of this paper is to highlight the utility of satellite remote sensing for monitoring environmental phenomena including biophysical parameters that are relevant for biodiversity and conservation.

Figure 1: The desiccation of the Aral Sea from 2000 to 2013 as seen from the MODIS instrument. Images courtesy of the Earth Observatory (http://earthobservatory.nasa.gov/).

1.1. What is Remote Sensing?

Remote sensing is defined as making observations of an event or phenomena without physically sampling it. Typically this is done with instruments and sensors mounted on anything from poles extended over a cornfield, to airplanes, to satellites orbiting the Earth. The sensors have characteristics that allow them to detect and record information regarding the emission and reflectance of electromagnetic energy from a surface or object. That information can then be represented visually on a screen or paper map or used in data analysis to inform decision-making.

The portion of the electromagnetic spectrum recorded is determined by the design of the instrument. For example, a digital camera uses light (electromagnetic energy) reflected off of the subject and its surroundings to create the image (figure 3). Other instruments use portions of the electromagnetic spectrum that are not visible to the naked eye but can be used to interpret things about the feature being observed, such as health of the vegetation or temperature of the ground. A benefit of remote sensing instruments is that they allow for the uniform collection of observations even in areas that may not be easily accessible on the ground. Historically, observations from remote sensing have been used not only for one-time maps of a given area but also for monitoring the changes in the area through time. There are a variety of measurements available from remote sensing that enable a greater understanding of the geography, climate, vegetation, and status of ecosystems within a study area.

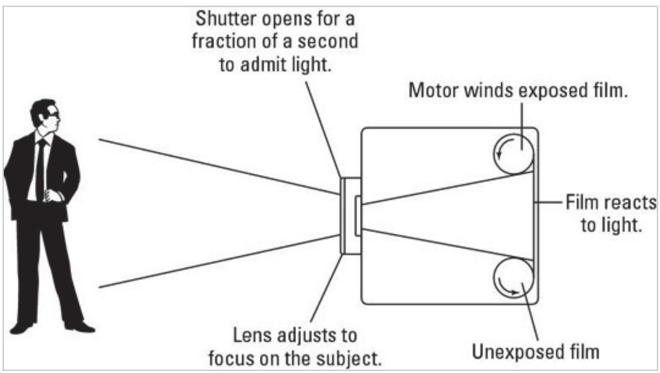

Figure 2 The physics of photography as an example of how remote sensing works to capture and image.

There are two different types of remote sensing instruments: passive and active. Passive sensors generally use the sun as an illumination source and analyze the reflectance information returned from the surface below. A digital camera is an example of a passive remote sensing instrument. Active sensors, although similar to passive sensors, not only collect and analyze the reflectance information; they also produce the illumination source used to take the measurement. A system such as "Laser Interferometry Detection and Ranging" (LiDAR), an example of active remote sensing technology, uses lasers to emit a pulse of energy to the ground and record the "return" or bounced back information to determine the height of a building or tree on the ground. Data from both active and passive sensors can be used for applications such as mapping landcover, habitat for animals, and other environmental applications.

There are a variety of remote sensing instruments used for Earth observation. These sensors can obtain unique information about the surface depending on their attributes. Each sensor has a unique design that gives it a specific temporal, spatial, and spectral resolution. Temporal resolution refers to the time it takes for the sensor to return to a location, spatial resolution describes the minimum size of feature that can be distinguished with the sensor, and spectral resolution characterizes the specific wavelengths of energy the sensor will record.

Remote sensing resolution

Temporal resolution *refers to the time it takes for the sensor to return to a location. For example, the Landsat satellites collect observations of the same spot on Earth once every 16 days.*

Spatial resolution *describes the minimum size of feature that can be distinguished with the sensor. For example, NASA's MODIS instrument can describe an area as small as 250*m^2 *(5.4 ha) in size, whereas Soil Moisture Active Passive (SMAP) mission will measure soil moisture for an area 9*km^2 *in size.*

Spectral resolution *characterizes the specific wavelengths of energy the sensor will record. For example, the SORCE satellite measures x-ray, ultraviolet, visible, near-infrared, and total solar radiation to address questions around issues of long-term climate change, natural variability and enhanced climate prediction, and atmospheric ozone and UV-B radiation.*

The different types of resolution impact the applications that are possible with each sensor. For example, the United States Department of Agriculture (USDA)'s National Agriculture Statistics Service (NASS) uses information from multiple sensors at various resolutions to produce crop specific yield estimates (http://nassgeodata.gmu.edu/CropScape/). Information from thermal sensors is used to detect wildfires for the entire globe on a daily basis. This information is provided to resource managers through web based geographic information systems for allocation and mobilization of resources (http://firms.modaps.eosdis.nasa.gov/firemap/). Very fine spatial resolution data have been used to identify ash trees in forests in the eastern United States (Pontius et al. 2008) and mangrove trees in the Galapagos Islands (Heumann 2011). In addition, data fusion methods have been used to combine multiple remote sensing sources for habitat mapping for migratory birds (Swatantran et al. 2012).

The development of electronic technologies has enabled expansion of remote sensing capabilities in two primary ways. First, the wide availability of electronic mechanisms and computer systems has reduced the overall cost of building, operating and analyzing the data from remote sensing instruments. This has resulted in an exponential increase in the amount and diversity of data available to researchers and application managers over the past few decades. Second, the technologies have resulted in increasingly smaller sized components that enable inclusion in a small package that can be mounted on an airplane or satellite for widespread data collection. Advances in solar panel and battery technologies have resulted in increased power availability to the instruments and high capacity computer hard disk drives enable storage of more information. Finally, widespread availability of high- speed internet service allows the information that has been collected to be distributed in ways that were unimaginable a decade ago.

Two major applications of remotely sensed data involve collecting information on weather/climate, and land cover. Changing climate and land cover conversion are primary drivers of biodiversity change (Currie et al. 2004, Francis and Currie 2003, Field et al. 2009, Turner et al. 2003). The USAID funded initiative "Central Africa Regional Program for the Environment" (CARPE) uses remotely sensed data to monitor landcover and changes in landcover over time.

Weather and climate both refer to conditions of the atmosphere; however, they occur on differing time scales. Weather is the condition of the atmosphere at a particular point in time (over hours or days). The short-term observation of atmospheric variables such as precipitation, cloud cover, and temperature with satellites make up weather observations. Climate is the atmosphere's long-term condition, which can be monitored using observations of the average weather for a particular location over an extended period of time. Remote sensing can also be used to observe parameters that describe both weather and climate. For example, the thermal bands of remote sensing instruments are useful for obtaining surface temperature over long periods of time.

1.2. What is Biodiversity?

Biodiversity is the distribution and number of species within a given area, including species assemblage and ecological communities (Turner et al. 2003). Two of the most common ways to

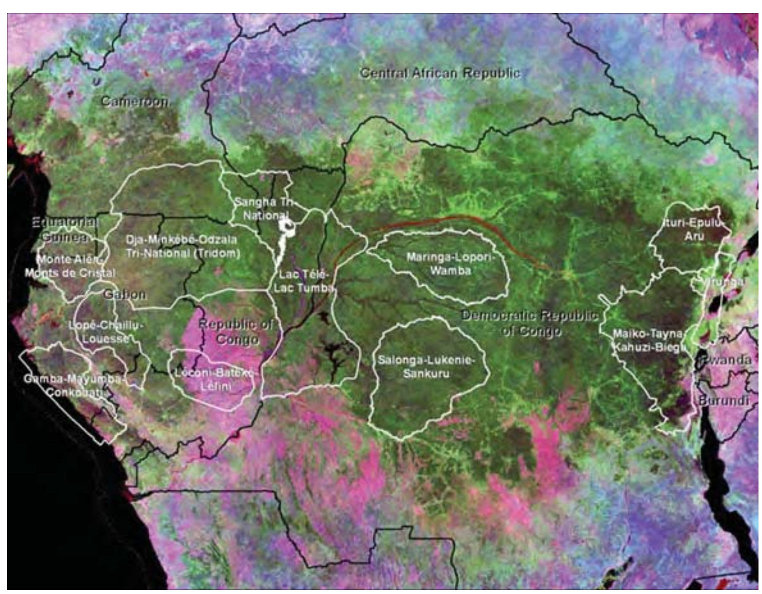

Figure 3 The CARPE study region with boundaries shown in white outline.

characterize and quantify biodiversity are species richness and evenness (Purvis and Hector 2000). Species richness is defined by the number of species present in a location, while evenness is a measure of species distribution across a region. Ecosystem attributes such as structure, composition, function, climate, and primary productivity determine the biodiversity of an ecosystem (Noss 1990, Turner et al. 2003, Pettorelli et al. 2011). Ecosystem structure refers to the organization and pattern of an ecosystem, for example whether the ecosystem is fragmented by development or land cover conversion. Composition refers to the diversity of species within the ecosystem, which includes genetic and species diversity. Function refers to the processes that take place and the rate of those processes within an ecosystem. Finally, primary productivity is the rate of energy conversion into organic material through photosynthesis.

Biodiversity is not globally uniform. Instead, biodiversity generally increases with decreasing latitude, with land around the equator having the highest biodiversity (Gaston 2000, Willig, Kaufman and Stevens 2003). The latitudinal gradients in biodiversity are greater in the northern hemisphere than in the southern hemisphere. This is partly attributable to the greater area of land in the northern hemisphere.

Over the last several decades, global biodiversity loss has been occurring at unprecedented rates, primarily due to human activity and increased demand for natural resources. The current rate of species extinction is estimated to be 100 to 1000 times the rate of extinction before humans dominated the landscape, and future projections estimate that rates of species extinction could be 10 times the current rate (Pimm et al. 1995, Pimm and Raven 2000). Anthropogenic impacts on ecosystems range from changes in land use to alterations of the biogeochemical cycle. Between the years 1700 and 2000, there has been a transformation of the biosphere as a result of the conversion of wild or unmanaged land area to pasture and cropland. Currently, 40 percent of all ice-free lands are directly used for agriculture, urban settlement, or related purposes (Ellis et al. 2010).

The resources available for conservation are limited, especially given the magnitude of global threats to biodiversity. Consequently, conservation practitioners have established systems that focus resources by identifying priority ecosystems based on criteria such as high endemism and level of threat. For example, Myers et al. (2000) used species endemism and habitat loss as criteria to identify 25 ‘hotspots’ where conservation would provide the greatest benefit to biodiversity given limited conservation resources (Figure 4). Organizations such as the World Wildlife Fund, Birdlife International, and Plantlife International have also identified priority regions based on various criteria to help them focus their resources.

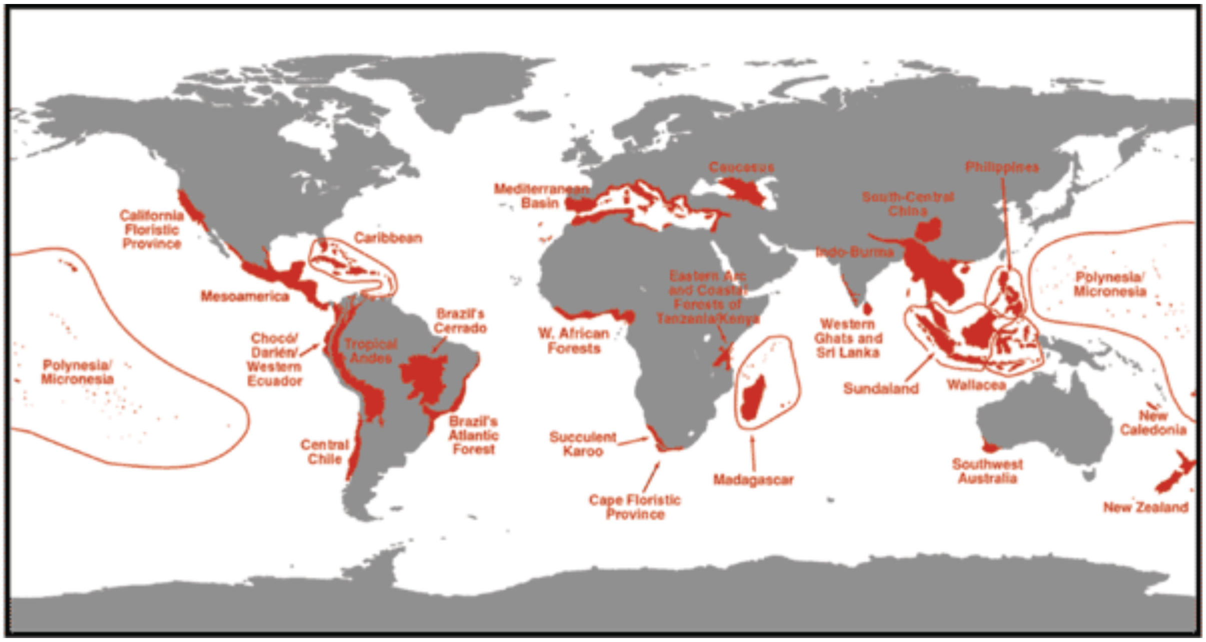

Figure 4 Hotspots of biodiversity as developed by Myers et al, 2000.

2. Remote Sensing and Biodiversity

A common method used to monitor biodiversity is the identification of indicator species, which can serve as proxies for the environmental conditions within a given setting. Noss (1990) identifies seven qualities that an indicator species should have in order to be effective: they should "be sufficiently sensitive to provide early warning of change; distributed over a broad geographical area or otherwise widely applicable; capable of providing a continuous assessment over a wide range of stress; relatively independent of sample size; easy and cost effective to measure, collect, assay, and/or calculate; able to differentiate between natural cycles or trends and those induced by anthropogenic stress; and relevant to ecologically significant phenomena." Indicator species can be chosen for a number of spatial scales from the regional level to the genetic level and can often be observed using remote sensors.

The geography of the Earth is not uniform; Olson et al. (2001) divide the terrestrial surface into 14 major ecoregions, with 867 distinct sub-regions, each sharing similar species, ecosystem dynamics, and climatic conditions. An example of the ecoregions of North America is shown in figure 5. The characteristics of the ecoregion and the feature/phenomena being investigated will help determine which remote sensing instrument can be used. For instance, the Landsat instruments have been operating for more than 40 years at spatial resolutions from 30m – 60m. These instruments view the same area on the ground every 16 days, producing data that are useful for investigating landscape changes over long periods of time, from years to decades. However, the temporal resolution of these instruments is not beneficial for a study that needs information about changes taking place daily. Instead, a study that needs daily data may opt to use a coarser spatial resolution instrument such as the Satellite pour l'Observation de la Terre - Vegetation (SPOT VGT), Moderate Resolution Imaging Spectroradiometer (MODIS), or Advance Very High Resolution Radiometer (AVHRR), which views the Earth with a wider swath every day at a lower resolution (Xie, Sha and Yu 2008, Kerr and Ostrovsky 2003). The coarser resolution is required to see the same spot on the ground every day.

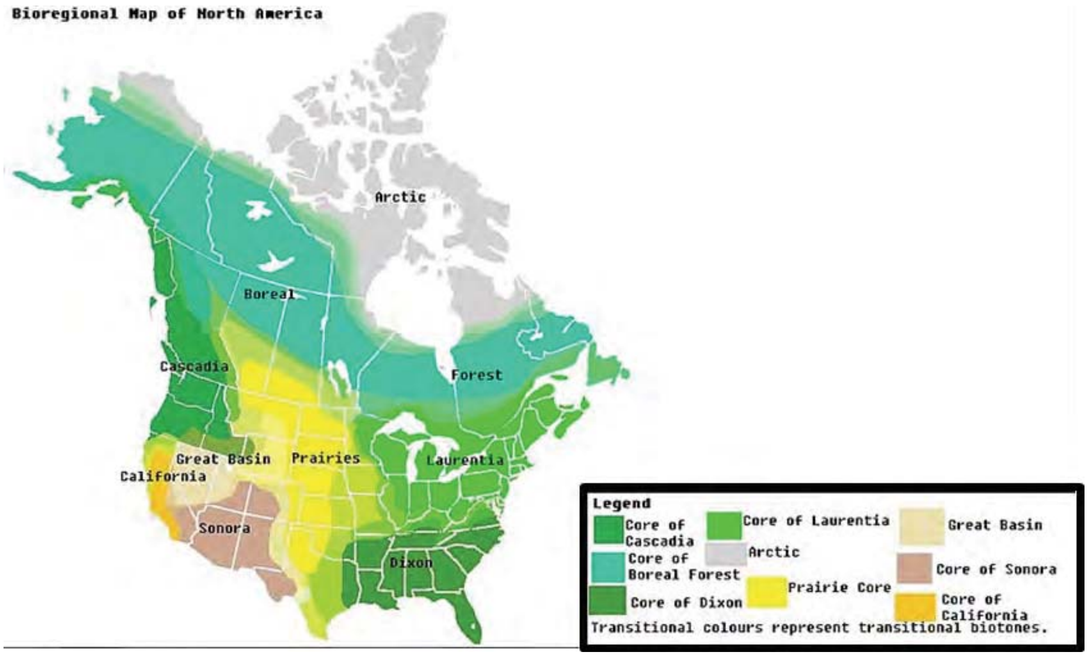

Figure 5 Ecoregions of North America Olson et al.

Remote sensing can be used to analyze static and temporally varying parameters. Land cover classification, where the Earth's surface is categorized into cover types is a common way in which satellite remote sensing can be used to study a static variable. Conversely, using remote sensing to analyze the temperature of the land surface is a temporally varying parameter.

There are two ways that remote sensing can be used to gather information about biodiversity: directly and indirectly (Turner et al. 2003). The following discussion will include both direct and indirect methods using temporally varying and static parameters.

2.1. Direct Remote Sensing Methods

The direct method uses remotely sensed data to quantify the actual species of interest, the way species are grouped, or characteristics of their habitat. This information is usually derived from the ground using surveys and other studies that allow the researcher to observe the species directly. A remote sensing variable can also directly show the species or habitat of interest. There are various remote sensing instruments that can be used to gather information about biodiversity for particular species. In order to obtain direct measurements, the remote sensing instruments must have a high spatial resolution and need to be used on species that are large enough to be distinguished with this data (i.e., trees, not plants) and that do not move around (i.e., ash trees, not elk herds). These instruments' products are typically commercially available (Table 1); in most cases, these data are not continuously collected but rather are collected in response to specific data requests.

Table1: Remote sensing instruments and products for biodiversity studies, direct methods. Examples below highlight high resolution imagery that is available from government and commercial.

Instrument	**Resolution**	**Type of data**	**Data availability**	**Collection frequency**	**Applications**
GeoEye – 1, IKONOS, Quickbird,	0.4m – 3m	Panchromatic and Multi-Spectral	Commercial	On demand	Quantification of area of habitat, quantification of area

World-View					changed, direct identification of trees
SRTM	30m – 90m	Radar Interferometry	Free	Static dataset from Feb. 2000	Elevation, slope and aspect; vegetation structure
SPOT, EO-1	10m – 30m	Multi-Spectral	Free (with restrictions)	On demand	Validation of coarse resolution products, quantification of area of habitat or change
GLAS, LVIS, MABEL, SIMPL, GLiHT	1m – 80m	LiDAR	Free (by agreement)	Historical – infrequent	Elevation, vegetation structure

An example where high-resolution imagery was used for direct measurements of biodiversity was the use of IKONOS (1m panchromatic and 4m multispectral) to accurately map mangrove forests in the Caribbean (Wang et al. 2004). Using the high-resolution imagery and land cover classification, Wang et al. (2004) distinguished with 94 percent accuracy between mangrove and non-mangrove vegetation as well as distinguished between red, black, and white mangrove species present in the study area. Similar work identifying mangrove species has been done in the Galapagos islands (Heumann 2011).

Figure 6 UAV helicopter with a camera mounted on the bottom (http://mdpi.com).

Direct remote sensing methods can also provide information that can distinguish between plant and tree species remotely. New technologies in both sensor design and the development of Unmanned Aerial Vehicles (UAVs) have resulted in rapid development of capabilities for fine scale tree and plant canopy characterization. Small remote-controlled helicopters (figure 6) have been outfitted with high-speed digital cameras that can take a high volume of images in a short time frame. These images can be processed through software to produce three-dimensional views of the surface or several levels within a tree canopy (Dandois and Ellis 2010, Mathews and Jensen 2013). The technologies used are affordable, lightweight and easily transportable. Applications of UAVs are in the early stages of development but there are clear implications for plant species identification as well as use in habitat identification for animal species.

There are significant limitations with the currently available remotely sensed data for direct remote sensing. First, very fine resolution imagery is required for most applications. This imagery may not be available over the region that is being studied. Second, acquiring new imagery can be quite costly, in some cases costing thousands of dollars per scene. Third, algorithm development for species identification is in its infancy and will still take substantial time to develop; in most cases, species identification is limited to large plant species (trees and large areas of homogenous cover) as it can be difficult to nearly impossible to identify even moderately sized mammals in remotely sensed data.

2.2. Indirect Remote Sensing Methods

The indirect method uses remote sensing to measure parameters that are known to influence biodiversity and statistically relate the parameters to the abundance of biodiversity. This method uses proxy information to monitor or to predict biodiversity. It is important to note that using proxy information does not measure abundance or species of animals but instead measures attributes large enough to be observed by remote sensing, such as the characteristics of the vegetation that an animal may inhabit or the climate in the region of interest. This can provide insights into habitat quality and the probability of finding a species in a particular location, predictions that can then be confirmed with site-based research.

Remote sensing instruments provide a variety of products that are useful for indirect, monitoring of biodiversity (Table 2). One widely used product is the vegetation index. Vegetation indices (VIs) are derived measures that use ratios of 2 or more spectral bands to normalize or minimize noise in the spectral dataset. VI's can provide information such as the density of vegetation at a particular location and time and its photosynthetic capacity (Myneni et al. 1995, Huete et al. 2002, Huete et al. 2006). Vegetation has unique spectral reflectance properties; it absorbs energy in the visible

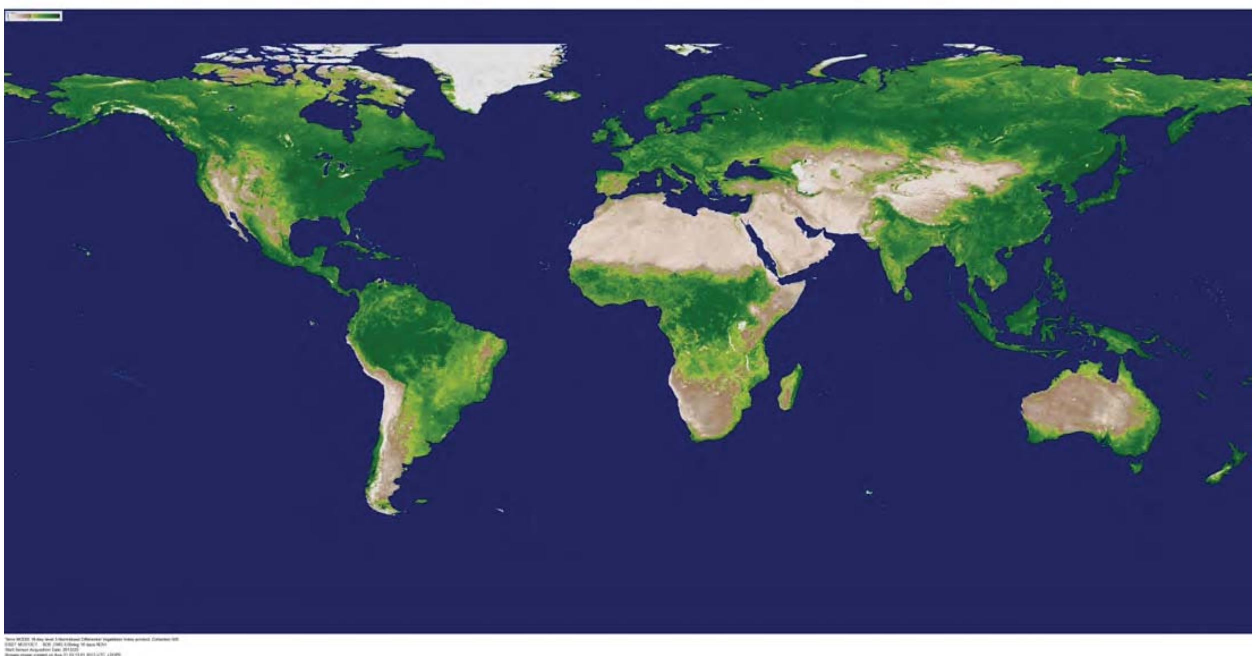

Figure 7 Global monthly NDVI from the MODIS instrument August 2011.

wavelengths while reflecting energy in the near infrared wavelengths. This characteristic can be utilized to create various vegetation indices which are mathematical combinations--ratios-- of differing wavelengths of energy (Cohen and Goward 2004). One commonly used index is the Normalized Difference Vegetation Index (NDVI), as seen in figure 7.

The NDVI is useful for long-term biodiversity monitoring because NDVI data sets can be assembled and inter-calibrated in a non-stationary way and used to evaluate changing ecosystem productivity through time. NDVI has been established as a crucial tool for assessing past and future population and biodiversity consequences of changes in climate, vegetation phenology and primary productivity (Pettorelli and Brown 2006, Pettorelli et al. 2011). There is a direct relationship between NDVI and gross primary production (Myneni et al. 1995, Pettorelli and Brown 2006, Pettorelli et al. 2011). This doesn't mean the NDVI is directly related to Net Primary Productivity (NPP), because similar NDVIs can have dissimilar respiration, and there's no simple way to accurately measure respiration.

Table 2: Remote sensing instruments and products for biodiversity studies, indirect methods.

Instrument	**Products for indirect remote sensing**	**Proxy/Feature measured**	**Length of record**
Moderate Resolution Imaging Spectro-radiometer (MODIS); Advanced Very High Resolution Radiometer (AVHRR); Visible Infrared Imager Radiometer Suite (VIIRS)	NDVI[1] LAI[2] VCF[3] ET[4] Land Surface Temperature Active Fire detection Ocean Color and Temperature	Ecosystem function Phenology Percent vegetated area Surface energy Surface energy Disturbance Ocean productivity	Up to 30 years with multiple instruments (250m – 8km)
Thematic Mapper, Enhanced Thematic Mapper, Operational Land Imager (Landsat suite)	Land cover classification NDVI LAI	Fragmentation/cover type Ecosystem function Phenology	Up to 40 years with 4 instruments (30m – 90m)
Advanced Microwave Scanning Radiometer for EOS (AMSR-E); Soil Moisture Active Passive (SMAP)	Soil moisture	Surface moisture and wetness	Up to 40 years with multiple instruments at coarse resolution (25km to 140km)
Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)	Vegetation indices Ocean Color	Vegetation type/health Productivity, algal blooms	Specific to collection campaigns
1)Normalized Difference Vegetation Index (NDVI), 2)Leaf Area Index (LAI), 3)Vegetation Continuous Fields (VCF), 4)Evapotranspiration (ET)			

3. Historical Biodiversity Remote Sensing Projects

The correlation between biodiversity and ecosystem function is a highly investigated relationship. The aspects that can be studied with remotely sensed data can be separated into three categories: Weather and Climate, Aquatic and Marine, and Terrestrial. Examples of projects from each of these categories will be explained below.

3.1. Weather and Climate

Weather and climate play an important role in ecosystem function. Variability in these environmental parameters has the potential to impact biodiversity and subsequently, ecosystem integrity and services. Changes in climate over the last 100 years, with some of the greatest changes taking place within the last 50 years, have been well documented (IPCC 2007). Shifting weather patterns and the subsequent impact on the climate represent a major threat to biodiversity. The impacts of climate change on biodiversity need to be understood at local, regional, and global scales; an integrative approach that brings together large area information with local scale information will be critical for a more complete understanding of these impacts.

Table 3 shows some examples of remotely sensed data that have been used in climate studies. These climate parameters are obtained using a range of tools such as field observations, remote sensing, and through the use of data assimilation/modeling. There are more than 10,000 ground weather observation stations globally recording weather and climate parameters such as precipitation, humidity, and evapotranspiration (WMO). In addition to ground observations, remote sensing instruments can be utilized to get weather and climate information; for example, the Tropical Rainfall Measuring Mission (TRMM) records tropical and subtropical precipitation measurements .Observed measurements from remote sensing instruments and field observation stations can be used with careful calibration to generate models that can be used to project weather over the course of the next 10 days or even climate changes over the next 50 years.

Table 3: Remote Sensing Products related to Climate/Weather

Product:	**Description:**	**Length of Record**	**Instrument**	**Use:**	**Availability:**
Cloud cover	4km	30+ years	AVHRR[1]	Cloud pattern mapping especially in high latitudes	Global
Precipitation	4km	10+ years	TRMM[2]	Precipitation	Tropics and subtropics
Evapotranspiration	1km	10 years	MODIS[3]	Water and energy balance	Global
Surface Kinetic temperature	90m	10 years	ASTER[4]	Estimates of surface temperature	Global
Global Land Data Assimilation System (GLDAS)	1 degree and 0.25 degree	30+ years	Model that incorporates multiple observations	Precipitation, surface temperature, convective potential energy	Land north of 60S
Modern Era Retrospective-Analysis for Research and Applications (MERRA)	0.66 degree longitude by 0 .5 degree latitude	30+ years	Model that incorporates multiple observations	Reanalysis of satellite observed data	Global
1) Advanced Very High Resolution Radiometer (AVHRR), 2) Tropical Rainfall Measurement Mission (TRMM), 3) Moderate Resolution Imaging Spectro-radiometer (MODIS), 4) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)					

Changes in climate have already been observed and these changes are not geographically uniform (Figure 8). Mean surface temperatures have risen 0.74 °C globally with land temperatures showing faster changes than ocean temperatures (IPCC 2007). The diurnal temperature range is decreasing as colder nights become less frequent. The rate of warming in the last 50 years is double the rate of warming over the last 100 years. Changes in precipitation patterns have also been observed where precipitation is decreasing in the tropics and increasing at higher latitudes (those above 30°N). Considering the strong relationship between climate parameters and species diversity, these climate changes are already impacting biodiversity and will continue to do so in the coming decades Information on climate and weather derived from remote sensing and modeling will play an increasingly important role in biodiversity monitoring, especially in the context of global climate change.

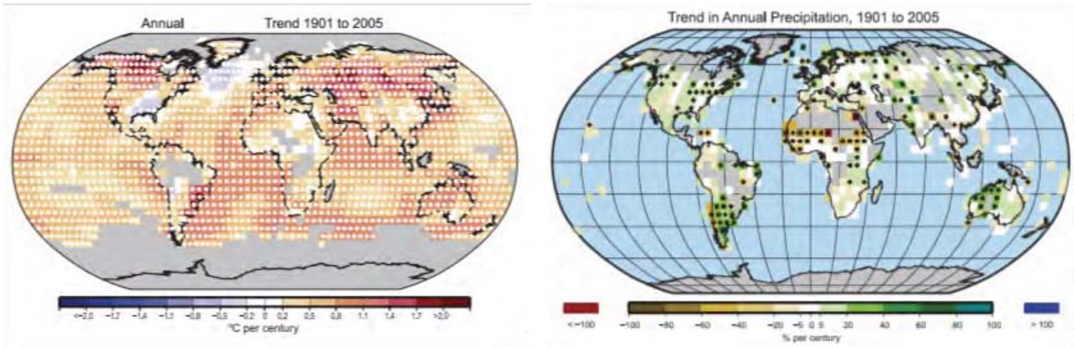

Figure 8 Annual trends in temperature and precipitation from 1901 to 2005, highlighting how changes in climate are not uniform. Reproduced from the IPCC, 2007 report from Working Group 1.

Satellite systems such as the AVHRR suite, NASA Earth Observing System and the Landsat suite of satellites have been collecting information on environmental and climate parameters for over 30 years. This historical satellite data is combined with ground station data in "reanalysis" projects such as the Modern Era Retrospective analysis for Research and Applications (MERRA) to produce daily climate parameters (wind, precipitation, temperature, etc.) that are more powerful than the individual measurements alone (Rienecker et al. 2011). Reanalysis data coupled with the wealth of new satellite missions coming online are set to provide measurements of atmospheric chemistry, ocean topography and circulation, soil moisture and increasingly frequent observations of land features at very fine spatial, temporal and spectral resolutions. These new tools will empower researchers to expand and continue building capacity to better detect and monitor biodiversity.

3.2. Aquatic and Marine

Human activities have highly impacted the water cycle over the last several decades; it is estimated that more than 50 percent of freshwater runoff is used for anthropogenic purposes, much of which is consumed in agriculture. Large water withdrawal not only has implications for the reservoir of water and the species within it, but can also impact ecosystem function and services. For example, the use of water for irrigation in semiarid areas can alter rates of hydrologic processes by increasing tropospheric water vapor, thus impacting climate and local ecosystems through increased precipitation in the surrounding region (Vitousek et al. 1997, Foley et al. 2005).

Freshwater ecosystems are some of the most highly threatened ecosystems globally due to the increases in unsustainable water extraction in recent decades. Inland waters and lakes in particular represent crucial habitat for aquatic biodiversity and provide critically important ecosystem services for human communities. Remote sensing can be used for the detection and mapping of lakes and rivers (Carroll et al. 2009, Lehner and Doll 2004), monitoring and characterization of changes in moderate to large lakes and rivers (Carroll et al. 2011b, Schneider and Hook 2010, Steissberg, Hook and Schladow 2005). These applications will be particularly important in assessing and projecting the impacts of climate change on inland waters and lakes.

Coastal ecosystems including coral reefs, wetlands, and mangroves are also at risk due to threats including habitat loss, pollution, and unsustainable harvesting of species. It is estimated that almost a quarter of all mangroves, sea-grass beds, and salt marshes have been lost over the last several decades (CBD 2010). Marine fishery resources are increasingly being degraded globally; one recent analysis found that almost three quarters of fisheries that were analyzed were fully exploited or over exploited (Brunner et al. 2009).

Remote sensing has successfully been used for coastal biodiversity applications; for example Landsat has aided in determining changes in coral reel habitat using time series analysis (Mumby et al. 2004) (Bertels et al. 2008). In addition, sea surface temperature measurements from AVHRR have aided in the development of a stress index (degree heating week), which analyzes hotspots (12-week rolling accumulations of the hottest sea surface temperatures for a location) to determine if corals are under thermal stress, which can lead to coral bleaching (Eakin et al. 2010). Overall, marine primary production has been mapped and monitored with coarse resolution instruments such as MODIS, SeaWIFS (Figure 9), and AVHRR (Butler et al. 2005).

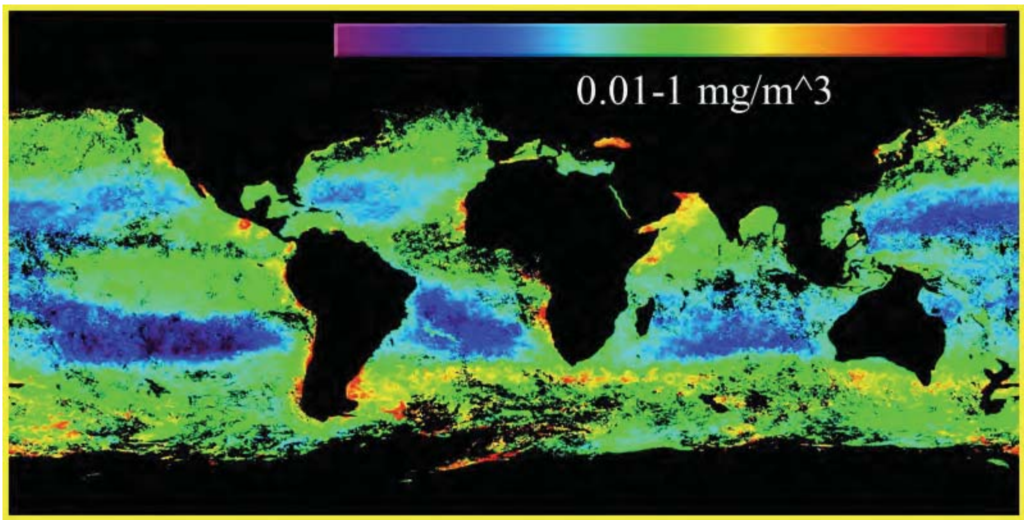

Figure 9 Global Chlorophyl: SeaWIFS R5, common-bin 12-day composite, Winter 2002 (Franz 2005).

3.3. Terrestrial

Terrestrial ecosystems have been a focus of remote sensing studies for several decades. Many algorithms have been used to demonstrate the ability of satellite data to discriminate features on the ground and to identify changes (both natural and anthropogenic) in landscapes over time. By linking the ability of remotely sensed data to characterize large areas with increasing definition to the conservation and biodiversity concerns results in a powerful analytical tool for scientists.

One method that has been used to estimate ecosystem function is the use of vegetation indices such as NDVI, where NDVI serves as an indicator of the function primary productivity (Turner et al. 2003). NDVI is correlated to parameters such as net primary production (NPP), which can serve as a proxy for ecosystem function (Kerr and Ostrovsky 2003). Higher index ratios represent more photosynthetically active vegetation or higher productivity and have been used to identify vegetated area, disturbance and regrowth (Pettorelli et al. 2005, Pettorelli et al. 2011, Hurlbert and Haskell 2003, White et al. 1996, Nagendra 2001, Oindo and Skidmore 2002).

Land cover classification (Figure 10) estimates the variation in land cover type within a study area. It can be useful for identifying potential habitats, therefore helping to predict the way species are distributed as well as species assemblages (Kerr and Ostrovsky 2003, Ozesmi and Bauer 2002, Fuller et al. 1998). There are a multitude of land cover products at multiple spatial and temporal resolutions (Carroll et al. 2011a, Hansen et al. 2003, Friedl et al. 2010, Defourny et al. 2006), including Vegetation Continuous Fields (percent tree cover), MODIS Land Cover and GlobCover respectively. Remote sensing can also be used to assess land cover change (Potapov et al. 2012, Margono et al. 2012, Hansen et al. 2008, Hansen, Stehman and Potapov 2010).

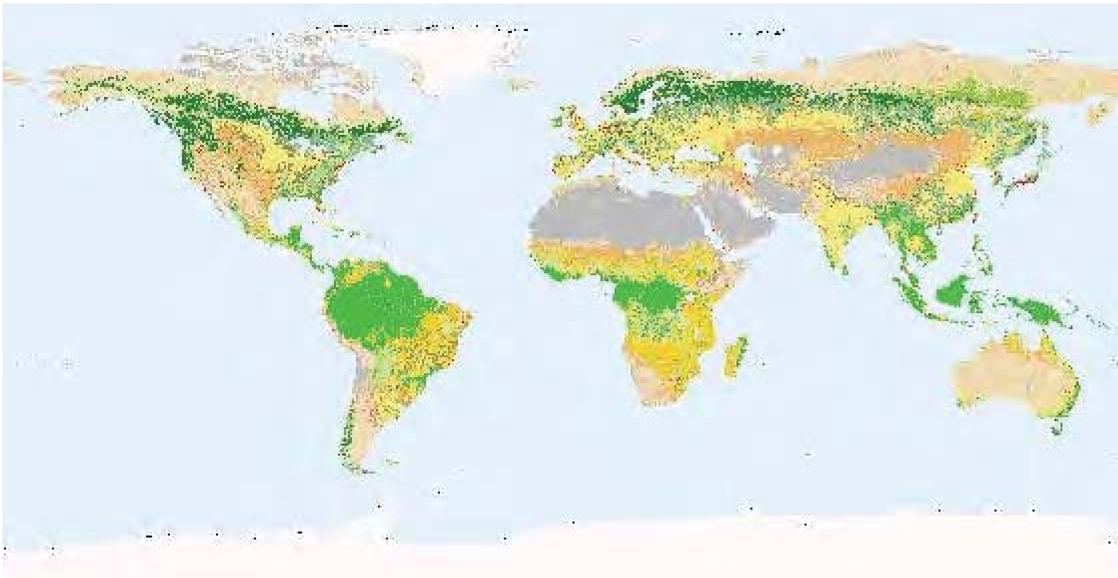

Figure 10 Global land cover product from MODIS. Product is generated annually and can be used to investigate consistency in land cover through time.

Not all instrument products available are strictly for analyzing vegetation. For instance, there is a soil moisture product produced by the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) onboard the Aqua spacecraft; these measurements will be continued with the upcoming Soil Moisture Active Passive (SMAP) mission. The soil moisture product is a global dataset providing daily soil moisture measurements (Njoku et al. 2003) which can be used to identify suitable habitat for species that require a certain amount of wetness to survive.

4. Remote Sensing Relevance to Monitoring of Species, Threats, Outcomes and Impacts

USAID prioritizes monitoring of four programmatically relevant areas: species, threats, outcomes and impacts. Each of these priorities can be investigated with remotely sensed data either through existing projects or through funding of developmental research on algorithms to analyze new and historical data. Below, we will discuss each of these priorities and offer suggestions for usage or development by USAID.

Direct ***species*** level identification of plants and animals is difficult with remotely sensed data. As discussed in section 2.1 and 2.2 of this report, there are a few examples of direct detection but this work is in its infancy and is ripe for investment for development of new algorithms and deployment of airborne instruments to acquire appropriate data. Significant limitations exist with this technology, especially as regards direct identification of animals. Greater success has been seen with using proxies such as identification of preferred habitat and monitoring the primary production in a known region for the species of interest.

Threats can be categorized as direct physical threats, such as anthropogenic disturbance, or indirect threats, such as climate change. There are applications for remote sensing and spatial analysis for both of these categories of threats. Direct threats can be measured by identification of human settlements and access points (i.e. roads/infrastructure) and by analysis of distances between the settlements and features of interest, markets for goods, and availability of subsistence resources. Climate change is measured using remotely sensed variables such as land cover, vegetation condition, clouds, temperature, precipitation, etc.

Outcomes can be tracked with remotely sensed data. For example, if policies or regulations are put in place in an area to preserve habitat, successive land cover maps can be used to measure the effectiveness of the policy. This method cannot directly attribute the cause of the preservation to the policy but the decision maker can infer that if change was occurring prior to the policy and ceased or declined after, then there may be a relationship. Monitoring of outcomes can be done to some extent with existing products, methods and technologies but would substantially benefit from investment in very fine (1m spatial resolution) data acquisition and investment in algorithm development for identifying fine resolution features such as selective logging and small human settlement. Improved human outcomes are not determinable from remotely sensed data; this will continue to require boots on the ground assessment.

Impacts are closely tied to outcomes in terms of what can be seen in remotely sensed data. The effect of variations in regulation and enforcement can certainly be seen on political boundaries. Examples such as the boundary between Haiti and the Dominican Republic (Figure 11), where the forests have been harvested dramatically in Haiti but not nearly as much in the Dominican Republic, are indicative of what may be possible with remote observations. Other possibilities such as monitoring the turbidity of rivers above and below areas with policies or regulations represent a potential area for development.

Figure 11 This image of the border between Haiti and the Dominican Republic illustrates how the forests have been completely denuded in this part of Haiti but remain intact in the Dominican Republic through government management and oversight.

4.1. Leveraging Existing Partnerships and Networks to Monitor Species, Threats, Outcomes and Impacts

USAID has a number of existing relationships with groups that work with remotely sensed data. The USAID launched Geocenter in 2011 to enhance and expand the agency's use of geospatial data and tools in support of development goals. Geocenter has implemented a number of web mapping services that incorporate geospatial data including some remotely sensed data. Tools such as the ArcGISOnline story maps showing the development credit authority (http://storymaps.esri.com/stories/usaidcredit/) enable policymakers at USAID to see where, geographically, resources have been invested. These services could be enhanced by including additional themed remotely sensed data products such as land use and land cover, changes in forest canopy, land degradation as well as time series data to provide a monitoring component to the platform.

SERVIR is a joint venture between NASA and USAID to develop and serve data products in support of environmental decision making in developing countries. NASA provides data to the platform for specific applications such as forest fire management and flood mapping. It also manages a call for science proposals to perform product and application development utilizing satellite data data products and tailored to developing countries. SERVIR has been successful in generating tools for individual countries such as Panama, but has had limited success in providing data and information that address the diverse needs of multiple-country regions in Africa that are characterized by many very different hazards, ecosystems, languages and cultures. The needs of individual countries can be quite specific and differ from country to country based on politics among other things.

The University of Maryland (UMD) has been supporting USAID efforts in central Africa through the Central Africa Regional Program for the Environment (CARPE) project. This project has developed land cover and land cover change products that have been used to monitor change in and around protected and conservation areas. UMD's Department of Geographical Sciences has a long history of product development and analysis using remotely sensed data. New product development such as the Global Percent Tree Cover derived from Landsat at 30m spatial resolution provide new insight into the rates and overall impact of deforestation on a global basis. Continued support of the development of new satellite data products for measuring and monitoring land cover change is essential to understanding the impact of policy and management decisions on the region and world.

The Woods Hole Research Center in Falmouth, Massachusetts several researchers who focus on the use of remote sensing in biodiversity research. Dr. Scott Goetz, for example, has pioneered the use of remote sensing to identify species habitat ranges in high latitudes, tropical forests, and in the conterminous United States. This Center works on conducting research and connecting the science to decision makers to ensure broad impact.

National Aeronautics and Space Administration (NASA) and United States Geological Survey (USGS) are federal agencies that fund and promote environmental research as well as supporting long term archives for geospatial data sets. Both agencies provide support to research organizations both internal (such as NASA Biospheric Sciences Laboratory) and external (such as universities) to create new data products from remotely sensed data. USAID has worked with these organizations in the past and could continue to leverage the partnerships. Additional relationships can be fostered with individual organizations that generate the actual data products.

4.2. Potential New Partnerships and Networks to Monitor Species, Threats, Outcomes and Impacts

There are many groups working on conservation and biodiversity issues both in the U.S. and internationally such as USAID, World Wildlife Fund (WWF), the Zoological Society of London (ZSL) and The Nature Conservancy (TNC). Many of these organizations use remote sensing data to inform program planning, implementation, monitoring, and evaluation. The Conservation Measures Partnership (CMP) was initiated in 2002 and has been developing standards for the practice of conservation among the various groups. This work is essential to be able to relate the success of projects between the organizations. Using common standards to measure success ensures that each organization is working towards the same commonly-defined goals. The practice of establishing common standards of measurement can be extended to remote sensing indicators.

The Group on Earth Observations (GEO) initiated the Biodiversity Observation Network (GEO-BON) in 2008 to function as a repository for biodiversity measurements. In the process, they have also developed common standards for data to make it portable across systems. GEO-BON is an extension of the larger

Global Earth Observation System of Systems (GEOSS), which has been operating for nearly a decade with the goal of achieving a more complete understanding of the status of and trends related to the world's living resources. BON is the first step toward bringing together stand-alone observations to enable greater synthesis of this information in a scientifically robust framework.

The CMP and GEO-BON are just two examples of ongoing efforts to develop not only datasets and databases but also partnerships and standards for the advancement of the science and management of conservation and biodiversity measurement/monitoring. Additional investment in engaging remote sensing product developers in these processes could enrich and enhance progress towards these objectives. The USAID can engage these groups by sending representatives to meetings or funding researchers to continue the development of biodiversity related maps and products.

5. Conclusions

Remote sensing is a tool that can provide a wide variety of measurements over large geographic areas and long time periods. The measurements can be collected by space-borne, airborne, or ground-based instruments and can be used to determine habitat types, climate and weather variables, as well as monitoring of changes in those variables over time. Historically, the data available from remotely sensed instruments has had moderate-to-coarse spatial resolution and hence was best suited for providing overview or regional-scale information. In the past 10-15 years, new technologies and major advances in computing capabilities have combined to generate new kinds of data that can be applied to more local phenomena. Use of remotely sensed data has expanded to include very fine spatial resolution information that can be applied to local issues, in some cases down to the individual tree level and certainly down to large field plot level. Commercial satellites such as IKONOS, WorldView and Quickbird have generated a new market for information to be applied to research and monitoring questions. Looking to the future, there are new projects that are set to come online in the next few years that will further expand the suite of capabilities from space-borne satellites. Hyperspectral instruments such as the future HySPIRI mission offer the possibility of generating new highly detailed maps that will support evaluation and monitoring capabilities of   USAID and other organizations.

Investments in interdisciplinary research will expand connections between the remote sensing community and the ecology community that performs biodiversity research. This will broaden and deepen the understanding and use of remote sensing parameters beyond simply land cover and NDVI.

Additional research is needed to continue to develop new algorithms for detecting phenomena of interest from remotely sensed data. Remotely sensed data will not replace the need for on-the-ground data collection. However, when used together with ground observations, remotely sensed data can provide a broader coverage than is possible simply with physical observations alone.

A follow-up document to this report, *Research Options for Application of Remote Sensing Approaches in Biodiversity Conservation and Development*, describes specific options that can be supported by USAID to advance the use of remote sensing in conservation and development projects.

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