ESTABLISHING AN ANALYTIC FRAMEWORK FOR CALCULATING CONSISTENT AND SENSITIVE MEASURES OF THE RATE OF BIODIVERSITY CHANGE

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ABSTRACT

The Convention on Biological Diversity's (CBD) VIth Conference of the Parties (COP) and the World Summit on Sustainable Development agreed to a target to achieve a significant reduction of the rate of biodiversity loss by 2010. The VIIth COP adopted a conceptual framework to facilitate the assessment of global progress toward 2010 and to encourage national and regional targets and indicators. However, most of the indicators identified are not and will not be adequately quantified at desired accuracy and with desired frequency by 2010. What is possible is the establishment of an analytic framework that can provide guidelines and baselines for biodiversity estimates that can steadily improve with time.

A judicious combination of remotely sensed data, Geographic Information System data, ground samples, and expert knowledge of species trends and species' use of habitats form a solid basis for assessing biodiversity. National development of sensitive, consistent, and affordable indicators that can contribute to the CBD global indicators requires access to a baseline set of global ecosystem, climate, topography, land cover, and human impact information. Fortunately, over the last ten years, a number of relevant information sources have become available. Such information, as well as appropriate methods for use, should be promoted and made highly accessible to countries and organizations that support the CBD.

The NASA-Non-Governmental Organization (NGO) Conservation Working Group is collaborating to evaluate and demonstrate the meaningful role remote sensing can play in developing biodiversity indicators to meet the targets specified. The Working Group members are evaluating indicators across a range of biomes and scales. The results are being synthesized in a handbook describing the use of remote sensing for monitoring the 2010 target to be published in 2006.

INTRODUCTION

In 2002, the Convention on Biological Diversity's (CBD) VIth Conference of the Parties (COP) established, and the World Summit on Sustainable Development reaffirmed, a target to achieve a significant reduction of the rate of biodiversity loss by 2010. The first step toward meeting this goal is to identify accepted practices for quantifying biological diversity within a practical, consistent, and scientifically valid analytic framework. Ideally, these practices should be designed so that indicators are scalable from local to national to global extents and so that the indicators are sufficiently accurate and precise to allow trends to be established.

The use of remotely sensed data is already recognized by the CBD's scientific advisory body as a critical component within a multi-level design for monitoring change through time (CBD 2004, Balmford 2005). Remote sensing provides repeated observation of the Earth's surface. Field sampling provides detailed local biological information for small areas. The integration of these two categories of data permits the establishment of a reliable, repeatable, and cost-effective basis for assessing changes in certain environmental parameters that are associated with biodiversity levels (Turner et al. 2003).

It is also recognized that having fully operational global indicators by 2010 is an enormous challenge (Balmford et al. 2005). So far, two indicators that either fully or partly employ remote sensing have been deemed suitable for quantifying change: the Forest Resources Assessment (FRA) and forest fragmentation. The FRA, which is administered by the Food and Agriculture Organization of the United Nations (FAO), measures forest cover change. The FRA has high political acceptance and is perceived to be well defined. However, as a global indicator, the FRA has not proven to be sufficiently consistent. (Matthews 2000, Mayaux et al. 2005). Forest fragmentation, as defined by Riitters et al. (2000), is also not fully developed for this purpose. Currently, the Riitters database represents a baseline, but it is not clear how to quantify change in fragmentation over time in a meaningful way and for all biomes. Thus, many challenges remain as we attempt to define clear and relevant definitions of biodiversity change (Newton and Kapos 2002).

Other remotely sensed indicators of biodiversity are still in the research phase or are only locally valid. More realistic expectations for 2010 monitoring include (1) defining and implementing a few indicators that take advantage of existing baselines, (2) expanding the use of biodiversity indicators currently under study or in local use to regional or global scales, and (3) encouraging the development of networks of expertise and local spatial databases for use in developing a coherent set of national indicators that possess global relevance. By 2010, it should be possible to have in place a set of methodologies for measuring change in biodiversity and a network of experts and centers that maintains local spatial databases. These same expert networks can facilitate the translation of local and national information to global indicator development.

A Working Group, with contributors from the American Museum of Natural History, Conservation International, Smithsonian Institution, The Nature Conservancy, The Wilderness Society, Wildlife Conservation Society, World Wildlife Fund (WWF), The University of Maryland, United Nations Environment Programme (UNEP)-World Conservation Monitoring Centre (WCMC), UNEP-Global Resource Information Database (GRID) Sioux Falls, and NASA, is attempting to describe applicable remote sensing technologies and methodologies for creating practical biodiversity indicators (Steininger et al. 2005). These methodologies will be described in a handbook written for national and regional technical advisors, NGOs, and researchers supporting the CBD and the 2010 goal.

The Working Group is concentrating on four of the global biodiversity indicators recommended by the CBD Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) for adoption (CBD 2004). These indicators are (1) trends in extent of selected biomes, ecosystems, and habitats (CBD 2005a), (2) coverage of protected areas (CBD 2005b), (3) threats to biodiversity, and (4) connectivity/fragmentation of ecosystems (CBD, 2005c). Other indicators will be discussed as either variant of these four or for testing in specific biomes. The indicators will be treated with regard to their potential use as national indicators. For each, the potential contribution of remote sensing will be outlined, while specifying (1) any assumptions determining use, (2) the need for auxiliary data, and the (3) the level of accuracy according to scale (local, national, and global) (Figure 1). The overall focus of the handbook is to clarify how remote sensing can contribute to the creation of national operational indicators in a parallel structure to the CBD's global indicators.

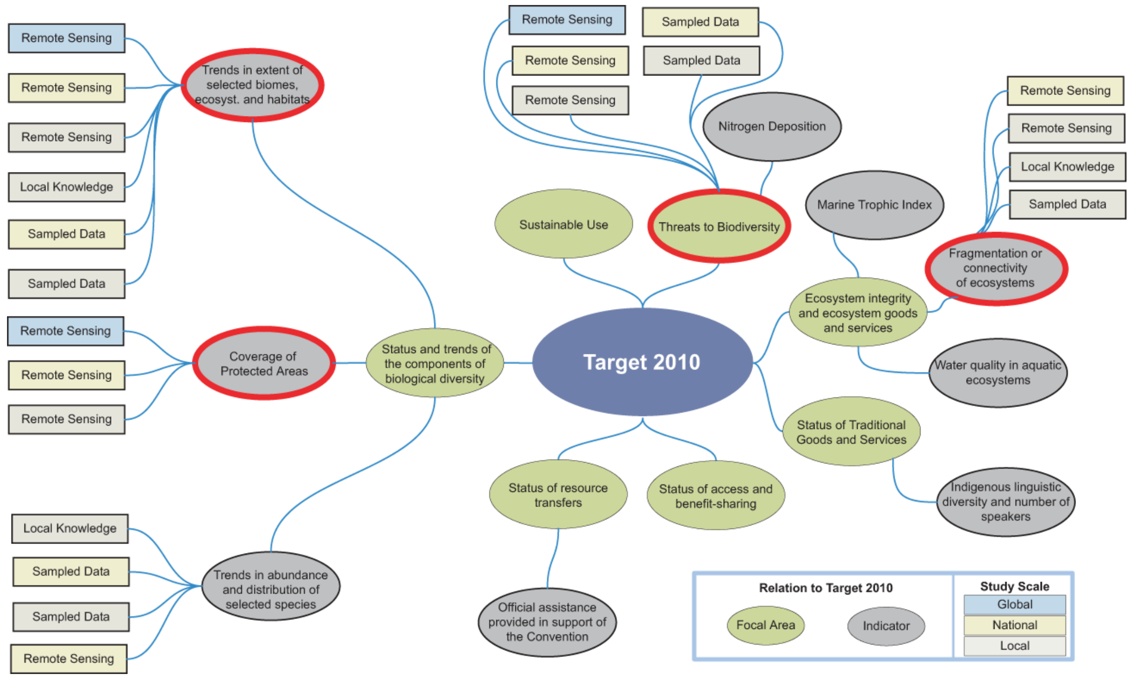

Figure 1. Implementation of CBD biodiversity focal areas and indicators for the 2010 target using remote sensing. The Working Group will concentrate on indicators outlined in red.

ANALYTIC FRAMEWORK FOR THE USE OF REMOTE SENSING

Remote sensing within a Geographic Information System (GIS) context can contribute to the monitoring of biodiversity at many different levels. Vegetation mapping from remotely sensed data can provide a globally consistent approach whereby biodiversity can be mapped in the past and projected into the future. Remote sensing has the potential to identify areas in which the ecological system has been changed and to quantify the nature of that change. In some cases, with the use of very high-resolution images, remote sensing can even provide species information. More commonly, however, remote sensing is used to identify land cover or conditions where species or ecosystems are likely to exist (Stauffer 2002). Information derived from remote sensing must be associated with local knowledge and field sampling of ecosystems and species within an overall analytic framework for monitoring biodiversity.

The use of ecoregions should be considered when monitoring biodiversity in a national or regional context. An ecoregion is defined as “a large area of land or water that contains a geographically distinct assemblage of natural communities that (a) share a large majority of their species and ecological dynamics; (b) share similar environmental conditions, and; (c) interact ecologically in ways that are critical for their long-term persistence” (Olson et al. 2001). By representing distinct biotas (Dasmann 1973 and 1974, Udvardy 1975), ecoregions act as analytical units whose borders represent transitions in habitats, species assemblages, ecological processes, threats, as well as human livelihoods. Since ecoregion monitoring data are nested in biomes, they can be referenced to CBD’s particular thematic Programmes of Work such as forests, dry and subhumid land, and inland waters. Therefore, ecoregions provide location information for the specialized goals and monitoring needs related to the various Programmes of Work within any one country. Furthermore, any given country is likely to contain more than one biome and probably shares species and habitats with neighboring countries. Ecoregions accommodate this biological reality (CEC 1997). Meanwhile, ecoregions can reinforce the goals and philosophy of the CBD’s Ecosystem Approach, which (1) emphasizes the use of appropriate spatial and temporal scales, (2) emphasizes the need to anticipate, plan, and act beyond political boundaries, and (3) involves and addresses the needs of the people who live in, and often share a common relationship with, target areas. Ecoregions and the ecosystem approach share a focus on the functional relationships and processes within ecosystems (Figure 2).

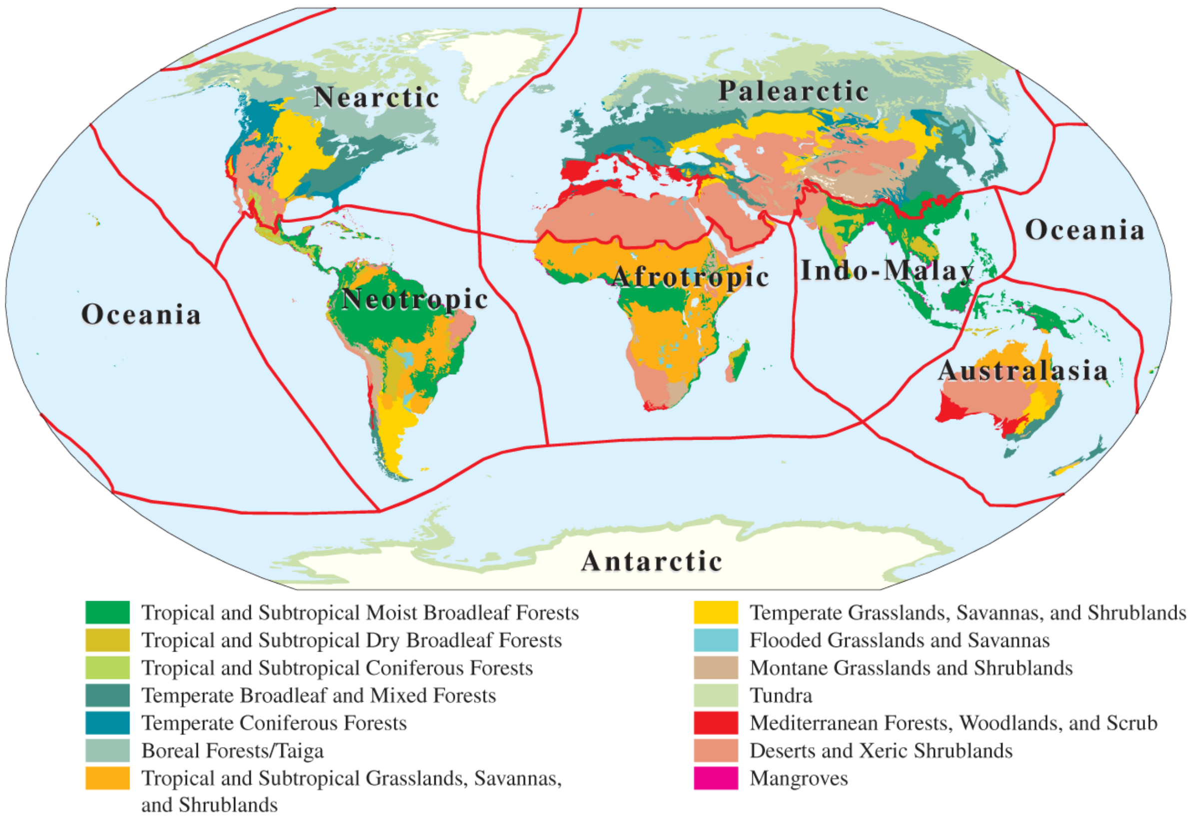

Figure 2. Ecoregions of the world (Olson et al. 2001).

Globally-Available Data Suitable for Use in Deriving Global and National Biodiversity Indicators

A remote sensing and GIS analytic framework within which to develop and implement global and national indicators should contain a basic set of global ecosystem, climate, topography, land cover, and human impact information. Taeishi and& Hastings (2000) documented the state of global environmental databases. Since 2000, a number of relevant global information sources have become available. WWF ecoregions (http://worldwildlife.org/science/data/terreco.cfm), the 1-degree Global Precipitation Climatology Project (GPCP) (http://precip.gsfc.nasa.gov/), 90-meter SRTM elevation data (http://srtm.usgs.gov/), circa 1975, 1990, and 2000 Landsat GeoCover data (http://glcf.umiacs.umd.edu/), MODIS data (http://edcdaac.usgs.gov/), SPOT VEGETATION products (http://free.vgt.vito.be/), and Gridded Population of the World (http://sedac.ciesin.columbia.edu/plue/gpw/) data are all currently available at no cost. Chief among the many products derived from remotely sensed data are land cover classifications that increasingly use standardized classifications or cross-referenced legends (FAO 2001), making comparability possible, although not easy. Products such as the vegetation continuous field models (Townshend et al. 2002) and phenological characteristics (Reed et al. 1994) are designed to facilitate the characterization of annual and seasonal vegetation change. These global databases provide a baseline set of data for developing global biodiversity indicators. Higher-level biodiversity models have also been developed, including the Conservation International Hotspots (http://www.biodiversityhotspots.org/xp/Hotspots) data set and regional and global collections under development by NatureServe (http://www.natureserve.org/).

One of the substantive differences between linked global/national data collections is the manner in which they are acquired. Some data sets follow a bottom-up collection model, with local and regional reporting entities contributing to a global collection, e.g., the World Data Base on Protected Areas (http://sea.unep-wcmc.org/wdbpa/). Other data collections, such as some raw satellite observations, are collected globally and then disaggregated to local and regional levels. The considerations of aggregation and disaggregation are similar to the issues involved in data scaling and are summarized in Table 1.

Table 1. Benefits and detractions of top-down and bottom-up models.

	Top-Down	Bottom-Up
Pros	Synoptic observations; standardized collections	Benefit of expert knowledge at point of collection
Cons	Lacks a "web of knowledge" or expert approach to information gathering Technology often requires duplicative collection mechanisms to avoid a "single-point-of-failure" model and ensure continuity, e.g., Landsat 6 Subsetting to the local level presents unique issues	Relies on aggregation to formulate a global data set; often difficult to validate individual inputs Many models rely on scaling from sample observations to global, with inherent inaccuracies and "multiplication of errors" problems

The remote sensing approach to global collection generally follows the top-down approach, but it is vastly improved through integration with bottom-up, *in-situ*, collection (Table 1). While incorporation of bottom-up interpretation, calibration, and validation into a remote sensing system enhances it by providing expert knowledge and analysis, it remains that digital analysis can often provide fast and cheap results for large areas, but accuracies can be low and resources required may be quite considerable.

Many sources of remotely sensed data are important locally or for specific biomes, from very coarse-resolution weather satellites to very fine-resolution photography and fixed platforms, such as balloons (Turner et al., 2003). All resolutions potentially have a place within multistage-assessment methodologies. Ikonos, Orbimage, Corona, Landsat, EO-1, ASTER, SPOT MS, SPOT VEGETATION, MODIS, AVHRR, Envisat, aerial photography, and videography allow the precision and accuracy of the biodiversity indicators to be optimized. At lower resolution (~1-km) and for larger areas, remotely sensed data provide an efficient tool for stratifying ecological systems. Higher resolution (~25-m) data can begin to describe structure and even species composition within ecosystems. Satellite remote sensing has been used to document the Earth's surface from space since the early 1960s. In some areas, aerial photography is available many years earlier and can be used to extend the time series of remotely sensed data further into the past. Sampled time series of remotely sensed images can effectively establish trends of change within an ecoregion analytic framework (Gallant et al. 2005).

Local Knowledge, Collections, and Spatial Data

The future of globally consistent biodiversity monitoring lies in the strength of global biodiversity networks. Remote sensing cannot be the sole source of information. Interpretation and meaning must be attached to the remote sensing derivatives through local knowledge and fieldwork. Successful scaling of remote sensing derivatives to local scales requires extensive local knowledge and local sampling programs. To use collections effectively, information on both date and location of samples is needed. An unfortunate trend is toward less collection of field samples, rather than more (Prather et al. 2004). To monitor change in biodiversity, collections must actively grow through time, so that shifting populations can be detected. To contain costs, it is vital that experts work within teams at the biome and ecosystem level, as biodiversity monitoring methodologies evolve to maximize the effective size of local biodiversity collections.

International networks supporting the monitoring of biodiversity already exist. The Terrestrial Ecosystem Monitoring Sites (TEMS) (http://www.fao.org/gtos/tems/) international directory has registered more than 2,000 long-term terrestrial monitoring sites. A wealth of information exists at these sites, but the biodiversity information across the network of sites is not organized in a fashion to readily support global biodiversity monitoring. The Global Biodiversity Information Facility (GBIF) (http://www.gbif.org/) is a comparatively new organization that is working to make the world's biodiversity data accessible anywhere to anyone through a consistent, standards-compliant mechanism. GBIF members include national agencies, museums, botanical gardens, universities and other organizations whose mandate is to collect and organize biodiversity information and specimens. The World Conservation Union (IUCN) (http://www.iucn.org/) and its Conservation Commons (www.conservationcommons.org) is a cooperative effort among conservation organizations to build partnerships that promote open access and fair use of data, information, expertise, and knowledge on the conservation of biodiversity. Among the evolving regional biodiversity networks is the Inter-America Biodiversity Information Network (IABIN) (http://www.iabin.net/). IABIN is developing a standards-compliant, Internet-based network to give access to scientifically credible biodiversity information currently scattered throughout the world. The Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) (www.fao.org/gtos/gofc-gold/) is actively involved in improving the quality and availability of observations of forests at regional and global scales and producing useful, timely, and validated information products from these data for a wide variety of users.

None of these networks or networks of networks function in a vacuum. Interrelationships among these and other networks are built into their mandates. It is necessary, but not sufficient, to facilitate the coordination and documentation of existing biodiversity information. Whittaker et al. (2005) discussed the inadequacies of existing physical collections, which can only be rectified through investment in establishing and expanding basic infrastructure at the national and local levels (Pilz et al. 2005). The international conservation NGO community is actively building national conservation capacity through programs such as the Conservation Measures Program (www.conservationmeasures.org). The coordination of this infrastructure development is a role for which the CBD Clearing House Mechanism (http://www.biodiv.org/chm/) is well suited through the participation and support of the Conference of the Parties and the technical groups (Laihonen et al. 2003).

SOME CONSIDERATIONS REGARDING SCALE

What are the effects of resolution on indicators and their interpretations or meanings? Whittaker et al. (2005) discussed the importance of spatial and temporal scalability. Biodiversity indicators must accommodate the measurement of species, ecological communities, landscapes, ecosystems, and biomes. An application of the same measure at these scales can have different interpretations that must be acknowledged and understood. Biodiversity information is collected and analyzed at different scales. The ability to use information at a local scale to infer information at a regional scale is an important part of a multi-level analytic design. Likewise, the ability to use high-resolution, remotely sensed data from local analyses helps improve coarse-resolution data for regional or national analyses.

Remote sensing is inherently scale dependent. What can be seen and analyzed with 1-meter data is different from 8-kilometer data. Pattern analysis of potential habitats from different resolution images can yield very different results (Lawler et al. 2004). Biodiversity characteristics that can be modeled with sensor data collected daily are different from those that can be modeled with data collected every ten years. Remotely sensed data have been globally available only since the 1970s. Most long-term trends require comparing biodiversity estimates collected at different scales (not to mention different methods). A distinct and critical advantage of remotely sensed data is the ability to reanalyze older data to meet evolving methodologies.

As demonstrated in Figure 3, the scale for measurement of a physical phenomenon is a function of time and space, as are the results obtained across scales (Figure 4). Aggregating locally measured phenomena implies that conclusions drawn by local observations will be valid at coarser resolutions. However, this principle does not necessarily hold true (see Figure 3).

An important advantage of remote sensing is that, in many cases, it can provide wall-to-wall, synoptic coverage of a phenomenon (the top-down approach from Table 1). In Figure 5, examples of remotely sensed imagery at three different resolutions, corresponding roughly to local, regional, and global scales, are provided. Recent technological developments have made it possible for high- to moderate-resolution sensors to obtain global coverage, bypassing some of the traditional disadvantages of using remote sensing for biodiversity and conservation analysis.

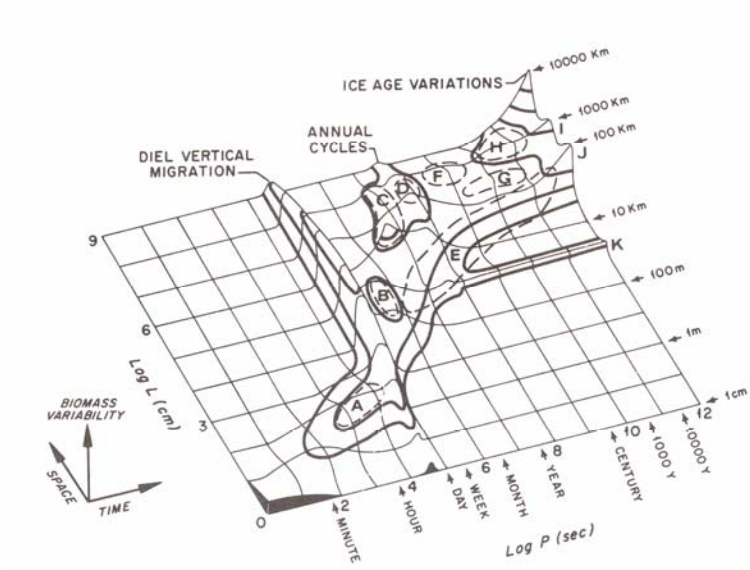

Figure 3. The Stommel Diagram, detailing time and space with zooplankton biomass graphed on the Z index. Phenomena range from the very local, "A," to island-effect, "E," to "biogeographic provinces," "H" (Haury 1978).

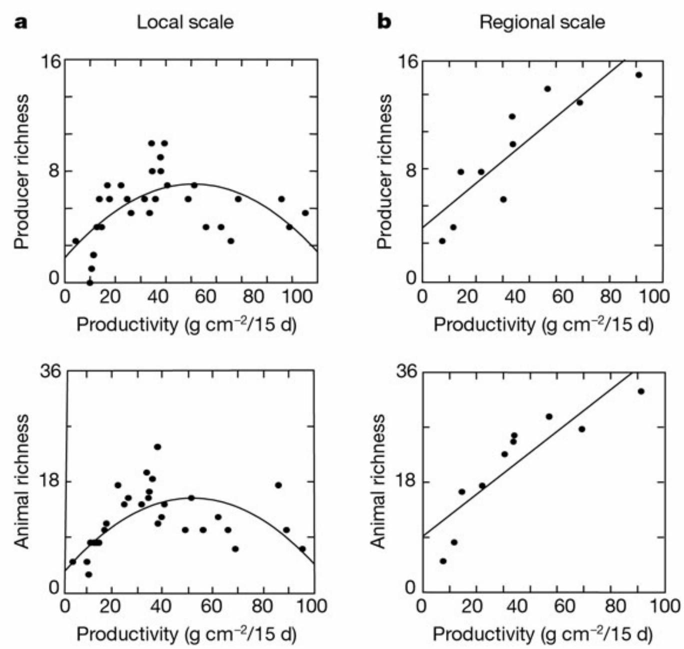

Figure 4. The commonly held theory that species richness increases with productivity, and then decreases as productivity approaches the high end of the scale, holds at the local (pond) level but not at the regional (watershed) level, where the relationship is linear (Chase and Liebold 2002).

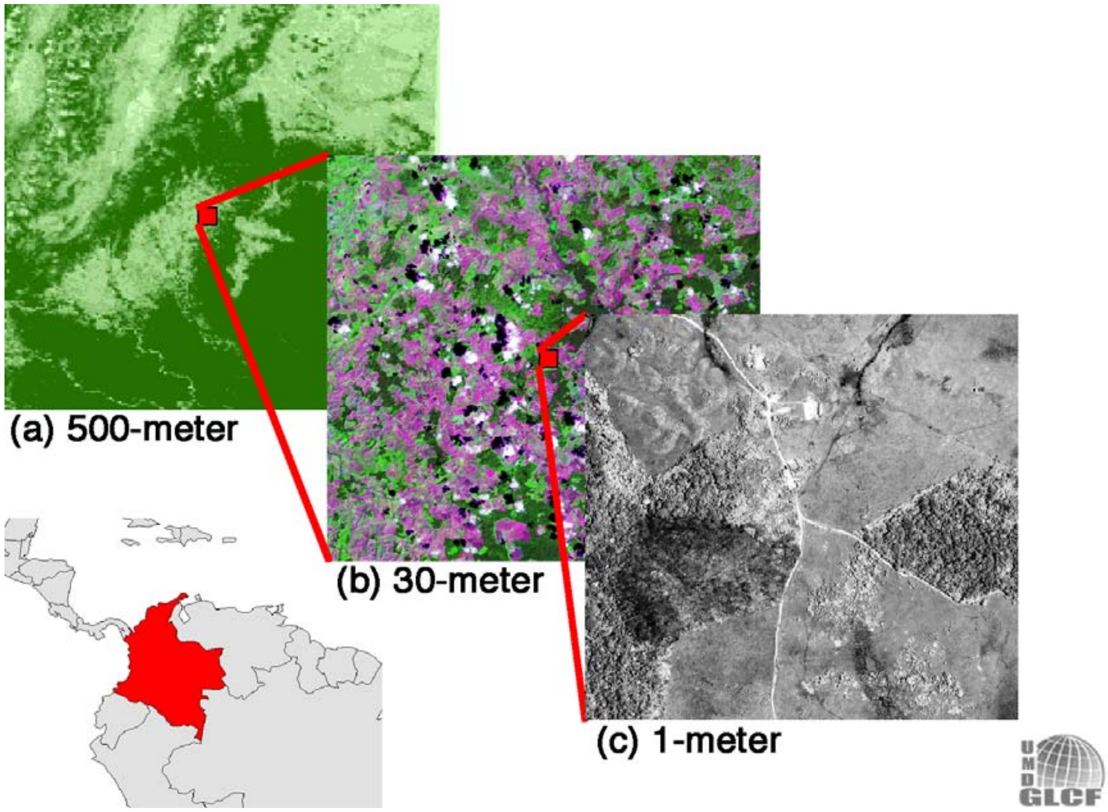

Figure 5. Three data sets at three different resolutions from the Global Land Cover Facility (http://glcf.umiacs.umd.edu/). Each provides insight into a separate phenomenon, e.g., (a) regional tree cover, (b) thematic variations in vegetative cover, and (c) road networks (GLCF, 2005).

In our remote sensing context, "scalability" refers to changes in the size and pattern of ecological phenomenon along with the resolution of the remotely sensed data. Increasing resolution often translates into increased cost, not so much due to data volume, but because of the importance of texture and the need for human interpretation of the information that exists in higher-resolution images. Texture, patches, corridors, and other fragmentation measures are particularly sensitive to changing resolution. The results of connectivity or fragmentation algorithms applied to high-resolution data will have, in most cases, a completely different interpretation than ones applied to low-resolution data. For example, a fragmentation index applied to 1-meter data may show landform/shadow texture and dominant species patterns, while application to 1-kilometer data may show broad land cover or vegetation condition patterns. To further confuse the issue, a fragmentation index in a grassland will need a different interpretation than one calculated for a forest. Indicators need to be thought of as piecewise models tailored to specific scales and specific biomes.

INDICATOR SENSITIVITY

Can we really measure change to a useful degree? Are the differences in the measurements greater than the measurement error? Are the indicators measured at different times really measuring the same thing? Indicators tend not to be direct measurements. Indicators are the results of models incorporating assumptions of scale, definition, distribution, habitat, communities, and relationships. Model calibration and validation measurement data may provide a very sparse representation of reality. The spatial and temporal models incorporated in the definition of indicators must be known so the trends can be evaluated. To be useful, indicators must be sensitive to meaningful change.

Indicators are acknowledged by the United Nations as important for evidence-based policy-making (Scott 2005). Indicators supporting the measurement of progress toward meeting the Millennium Development Goals

(MDG) by 2015 have received statistical scrutiny to assess their relevance and their comparability between places and times (Carraro et al. 2004). Carraro et al. identified current weaknesses in the MDG indicators as (1) data availability, (2) comparability, (3) definitional issues, and (4) methodological differences. For use in indicators, the data must not only be available but must also be analytically useful, that is, sensitive to change. To be analytically useful, indicators must have clear definitions; the clear definitions must be consistently applied; and it must be possible to operationalize the indicator. When operationalized, the methodologies used must not introduce definitional differences or biases. These characteristics hold for biodiversity indicators as well.

Availability of biodiversity data, as discussed earlier, is ultimately a local issue. Essential information about biodiversity can only be collected in the field by local experts. However, for selected biodiversity indicators remotely sensed data can extend knowledge of local samples to larger areas. Biodiversity indicators by their very nature are modeled through both space and time. This means that to achieve spatial distributions of species or species abundance assumptions of their distribution must be made. To quantify change in these distributions through time requires consideration of spatial and temporal interpolation, ecological models, or assumptions and autocorrelation (Henebry and Merchant 2002).

To achieve adequate spatial representation, temporal models are used to estimate species and habitat. Unfortunately, temporal and spatial scales are often confounded in biodiversity models. Without available data at appropriate scales, clear definitions, and consistent, operational methodologies, exact sensitivity to change cannot be estimated. Without knowing sensitivity, it is impossible to assess accuracy of estimates.

A scientific assessment of indicator needs for the 2010 target points out that three data points with confidence intervals are needed to establish a trend in the rate of loss of biodiversity. Confidence intervals will be difficult to establish for many of the indicators due to the confounding influences of the limited data record and modeling methodologies. Ideally, operationalization of the CBD indicators includes the definition of clear and consistent indicators with known statistical properties. Comparability is directly tied to what biodiversity change can be detected through time and what kinds of biodiversity can be detected and measured. Initial estimates may have high variances. However, if the indicators are produced within a consistent design, then as more information is accumulated over time, the accuracy and precision of the indicators will improve.

CONCLUSION

The dawn of the twenty-first century has seen maturation in the development of indicator typologies for evaluating biodiversity change. Significant strides have been made by CBD, the Millennium Ecosystem Assessment, Target 2010, and more recent initiatives dealing with effective management of biodiversity within protected areas (Hockings, 2005). Nevertheless, multiple challenges remain. One of the more consternating and publicly debated issue has proven to be the collection of verifiers to determine progress toward meeting internationally agreed upon goals (de Sherbinin et al. 2002). Remote sensing has great potential for use in verification.

For remote sensing to be effective in its contribution, it will be necessary for the conservation science community to turn its attention to some of the heretofore-unresolved assumptions inherent in biodiversity monitoring. How can the collection of local knowledge of biodiversity be encouraged and facilitated? How can access to data, such as remotely sensed data, be facilitated? How can biodiversity indicators be operationalized and validated? How can a biodiversity monitoring system be made sustainable (Watson and Novelly 2004)? One of the most challenging science issues in the near future will be how we address these questions within the context of ecosystem forecasting. The answers to these questions are complex and still evolving. These questions will probably not be put to rest by 2010. But this should not prevent supporters of the Convention from making progress toward a rational and long term monitoring system. Even now remote sensing can provide unique insight into CBD indicators such as "Trends in extent of selected biomes, ecosystems and habitats" and "Fragmentation/Connectivity." Close collaboration between networks of remote sensing and biodiversity community is key for the continuing evolution toward statistically viable and operational biodiversity indicators.

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