GRA Prospectus Project: Optimizing Design and Management of Protected Areas

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REVIEW OF PROJECT DESCRIPTION

Protected areas comprise one major type of global conservation effort that has been in the form of parks, easements, or conservation concessions. Though protected areas are increasing in number and size throughout tropical ecosystems, there is no systematic method for optimally targeting specific local areas for protection, designing the protected area, and monitoring it, or for guiding follow-up actions to manage it or its surroundings over the long run. Without such a system, conservation projects often cost more than necessary and/or risk protecting ecosystems and biodiversity less efficiently than desired. Correcting these failures requires tools and strategies for improving the placement, design, and long-term management of protected areas. The objective of this project is to develop a set of spatially based analytical tools to improve the selection, design, and management of protected areas.

In this project, several conservation concessions will be compared using an economic optimization technique. The forest land use portfolio model is an integrated assessment that measures investment in different land uses in a forest. The case studies of individual tropical ecosystems are developed as forest (land) use and preservation portfolios in a geographic information system (GIS). Conservation concessions involve a private organization purchasing development and resource access rights in a certain area and retiring them. Forests are put into conservation, and those people who would otherwise have benefited from extracting resources or selling the right to do so are compensated. Concessions are legal agreements wherein the exact amount and nature of the compensation result from a negotiated agreement between an agent of the conservation community and the local community. Funds are placed in a trust fund, and annual payments are made to local communities and regional/national governments. The payments are made pending third-party verification that the forest expanse and quality have been maintained.

RESEARCH PARTNERS

Recently Conservation International (CI) has established conservation concessions as a means to conserve biodiversity. CI accepts private donations and “invests” them in conservation concessions. The Field Museum of Natural History (Field Museum) has a research branch that conducts ecological classifications and rapid biological assessments. The Field Museum has been working with CI to prioritize areas for protection on the basis of ecological significance of habitat areas that contain large quantities of biodiversity. CI combines economics, finance, and negotiation with the Field Museum’s biological and ecological inventories to target areas for protection. Hardner and Gullison Associates, LLC (HGA) is an environmental consulting firm that assists CI with economic and ecological analyses and with negotiations for each concession. Finally, the Ecosystem Science and Technology (EST) Branch of the National Aeronautics and Space Administration (NASA) provides expertise in remotely sensed instruments and information and in the analysis of remotely sensed images in tropical environments.

At present, the first payment for the first concession has been made to the National Forestry Commission in Guyana. Several other project sites—in Perú, Bolivia, and Guatemala—are in different stages of the assessment and decision process. These four sites are the case studies for the USGS research project.

The Center for Applied Biodiversity Science (CABS) at CI, which has completed work in biodiversity measurement and protection prioritization, has developed large databases of remotely sensed and field-based data. Much of this information is in a GIS that is suitable for spatial analysis—a specialty of the USGS–National Mapping Division’s Center for Science Policy (CSP).

Research Goals

Together with CI–CABS and the other research partners, the CSP is developing an analytical tool to compare and rank protected areas for forest selection, design, and management. The economic framework will maximize conservation per dollar spent given a biodiversity standard or target. Included in the model is an assessment of three types of risk: misallocation of resources in the acquisition or protection of ecosystems, the physical chance of loss or negative change to the protected area, and the uncertainty around projections relating to threats and opportunities for conservation in a given area.

The forest land use portfolio model is an application of the expected utility model and assumes a state preference approach. It incorporates risk aversion into the decision framework. This type of economic model has not been applied to biodiversity and conservation problems. The model minimizes the difference between the expected payoff of a concession and the uncertainty associated with that payoff. This is an effective way to compare unlike resources in different parts of the world. Since funding for conservation concessions comes from donations made by private citizens, it is important to demonstrate that those donations secure the best use of tropical ecosystems.

Research Hypotheses/Questions

The following questions are the core for a set of testable hypotheses that will be evaluated over the life of the project:

- What are the most cost-effective types and scales of remote sensing information to use in protected areas?
- Can the goals of protected areas be met more effectively through increased and/or improved use of GIS, remote sensing, risk analysis, and economic models?
- How can spatially based risk management and economic theory be applied to protected area creation, design, and management?
- How can the forest land use portfolio model be applied to conservation and protected areas? What are its limits?
- Can the impacts of land use change be evaluated as a portfolio problem?

Progress Report

This project was funded to commence January 1, 2001. Since that time, a Memorandum of Understanding managing the cooperation between the USGS and NASA was written and signed; a similar Memorandum of Agreement between the USGS and the private research partners was also signed.

The first of the concession areas, the Parque Nacional Cordillera Azul in Perú, was created in 2001. This area was established in advance of our research, so we will be able to use the data collected there to build models and tools for future protected areas. The Field Museum and CI have continued to collect remote sensing and ground-tested data in Bolivia, Perú, and other potential future concession sites. The Field Museum has completed and published two Rapid Biological Inventories (Biabo, Perú, and Pando, Bolivia).

The USGS and HGA have agreed to investigate the suitability of the portfolio model to forest land-use and investment in protected areas. Data from several study areas—including various types of remote sensing, GIS layers, and socioeconomic indicators—are being collected and will be delivered to the CSP in batches.

An initial literature search has been conducted for the project; the resulting bibliography is being augmented continually. The next section outlines the economic models and ideas we will be using; the following section describes the literature review and annotated bibliography.

THE ECONOMIC MODEL FOR A LAND USE PORTFOLIO

Define V_k to be the market or nonmarket value of land parcel in location k, where k=1,…,K locations in a tropical ecosystem. Local physical conditions can affect V_k. Value is a function of the willingness to pay for an economic activity to occupy a parcel of land and represents land rent and any surplus that accrues in the forms of either consumer’s or producer’s surplus (Lind, 1973). Value can be based on market prices (private goods) and nonmarket benefits (environmental goods and services). Development pressures can cause environmental hazards (adverse physical changes due to human intervention and/or natural hazard) that can reduce V_k. Support for estimation of a change in land value is an environmental hazard probability that is a function of natural science process models and information that vary in accuracy and density of observations from region to region (Bernknopf and others, 2001). Where an environmental hazard is present for a land parcel, the total expected benefit becomes

$$V_{haz(k)} = (1 - p_{haz})V_k \qquad (1)$$

where p_{haz} = the probability of the hazardous event occurring.

The effectiveness of any specific remedy ψ_{eff}, including concessions, is uncertain for a specific site, where $0 \leq \psi_{eff} \leq 1$. There is no certainty that regulations can be enforced completely even though property rights have been defined completely. Lack of enforcement creates a risk to the regulatory authority. Combining hazard probability and concession yields a vulnerability assessment, γ, where γ = 1, . . . , Γ. Although their outcomes are uncertain, concession actions are taken to reduce the impact of the hazard on V_k. However, the decision to mitigate a hazard comes at cost C_{fc}. When a concession is undertaken, equation 1 becomes

$$V'_k = [(1 - \gamma)V_k - C_{cf(k)}] \qquad (2)$$

where $0 < \gamma \leq 1$, and $C_{cf(k)}$ is the cost of a concession in k.

The land use portfolio contains safe and risky assets. The portfolio can be described in terms of a proportion α_h of j activities that are h = 0 for vacant land (that is, a riskless asset), h = 1 for forest land developed with a safe land use, h = 2 for land with activities susceptible to specific hazards, and h = 3 for land with activities that are subject to specific hazards that have been mitigated. Land parcels subject to a hazard could suffer damage from development, and the use and future value of these lands would diminish. In these parcels, there is a risk associated with the benefits from the land use owing to the severity of hazard. In addition, benefits of concessions are uncertain because the effectiveness of the remedy is ambiguous; that is, when a hazard event occurs there could be a total loss or partial damage. The value of a forest land use portfolio A is therefore

$$V(A) = \sum_k \alpha_0 + \sum_k \alpha_h V_{jk} \quad h = 1,2;\ j = 1,\ldots,J \qquad (3)$$

where $V(A)$ is the value of the land use portfolio A, j is the potential land use, j =0,…,J, and α_h is the proportion of the portfolio in hazard class h. In locations that incur a concession investment, the value of portfolio A now becomes

$$V'(A) = \sum_k \alpha_0 + \sum_k \alpha_h V_{jk} + \sum_k \alpha_h V'_{jk} \quad h = 1,2,3;\ j = 1,\ldots,J \qquad (4)$$

where $0 < V'(A_{JK}) \leq V(A_{JK})$.

Economic Decisionmaking

It is assumed that the decisionmaking preference is to maximize the value of a forest land use portfolio and, where appropriate, to lessen development and environmental risk. The economic decisionmaker evaluates a forest portfolio with development risks defined in terms of objective probabilities and assumes rational behavior under risk. Information about the hazard and the effectiveness of loss avoidance contains uncertainty. In the decision problem, it is assumed that an economic action is to invest in a forest concession with or without loss prevention from development or natural hazards. This economic action is represented by an objective probability distribution of a property valuation $V(A)$ (Sinn, 1983):

$$R[V(A)] = \sum_{j=0}^{J} \sum_{k=1}^{K} p_k V_{jk} \qquad (5)$$

where $R(\cdot)$ is a function of preferences, p_k which are the probability that portfolio *A* will have value *V* associated with wealth W_k. In other words, the decisionmaker chooses an action out of the set of possible alternatives that brings about a probability distribution that maximizes the value of the preferences (Sinn, 1983). It is assumed that *V*(*A*) is a random variable that takes on a range of values with known probabilities p_k. So far we have developed this using a quadratic utility function. We believe that a state preference approach to the forest land use portfolio is better suited for this project. Our research has begun to develop this model. Until the state preference approach is fully developed, we are substituting the quadratic utility model. Consider a quadratic function that relates utility *u* to *V* in the following manner (Sharpe, 1970):

$$u_{jk} = a + bV_{jk} - cV_{jk}^2 \tag{6}$$

A summary of individual preferences is a utility function, and the decision criterion for these preferences is the expected utility criterion. The expected utility criterion is defined as the mathematical expectation of an end-of-period wealth distribution that is transformed into a distribution of utilities by means of a given utility function (Sinn, 1983). Define *EU*(*A*) as the expected utility of portfolio *A*:

$$EU(A) = \sum_{j=0}^{J}\sum_{k=1}^{K} p_k u_{jk} = \sum_{j=0}^{J}\sum_{k=1}^{K} p_k(a + bV_{jk} - cV_{jk}^2) \tag{7}$$

Expanding equation 7 yields

$$EU(A) = a\sum_{k=1}^{K} p_k + b\sum_{j=0}^{J}\sum_{k=1}^{K} p_k V_{jk} - c\sum_{j=0}^{J}\sum_{k=1}^{K} p_k V_{jk}^2 \tag{8}$$

where $\sum_{k=1}^{K} p_k = 1, \sum_{j=0}^{J}\sum_{k=1}^{K} p_k V_{jk} = E(A),$ and $\sum_{j=0}^{J}\sum_{k=1}^{K} p_k V_{jk}^2 = \sigma^2(A) + E^2(A)$

The expression for expected utility is

$$EU(A) = a + bE(A) - cE^2(A) - c\sigma^2(A) \tag{9}$$

where *EU'* > 0, and *EU"* • *0* (Lewis and Nickerson, 1989; Shogren and Crocker, 1991; and Quiggen, 1992).

LITERATURE REVIEW

The relevant literature for this project can be divided into four main categories:

- Remote sensing and GIS capacities, limitations, and applicability to protected areas
- Biodiversity classification, measurement, and prioritization
- Economic optimization, portfolio theory, spatial analysis, risk management, and decision analysis
- Protected areas creation and management

Obviously, these are broad topics with several journals devoted to each, and an exhaustive study of any one of them would take years. Here, we outline the state of research in each of the above categories and define the important research concepts from each topic, the state of the research, and how we will add to them. For this project, we focus on those aspects of the literature that are most critical—either in terms of technique, concept, or geographic relevance to the case studies.

Remote Sensing and GIS

The first stage of the project involves making decisions about which types and scales of remote sensing data to acquire. Thus, most efforts to date have been dedicated to this category. One of the major opportunities for decreasing the risk and increasing the cost-effectiveness of conservation is to optimize the amount, type, and scale of data used. Field observations and remote sensing are the two ways of gathering information about the condition of and threats to tropical forests ecosystems. Both provide information to help make decisions, and both bear a cost. The goal is to maximize the utility of the information acquired per dollar spent on it.

To reach this goal, we will research the many types of remote sensing data available. These might be from government (such as Landsat thematic mapper) or private (like Space Imaging Corporation's IKONOS) sources. We seek to determine the appropriateness of each technology on the basis of relative resolution, costs and scales of data, and the sensitivity to the physical structures that we will need to image. There are likely to be other constraints as well; for example, some technologies are more capable of penetrating the cloud cover that is so prevalent in the tropics.

Since data costs increase with scale and resolution, we are looking for "thresholds" in the relations between these variables. We wish to know at what scales information becomes useful and at what point buying higher resolution information brings diminishing returns. A similar dynamic exists in the search for the ideal number of different types and combinations of data to supply. This aspect of the project is very similar to a number of USGS–CSP projects that combine economic analysis, optimization, risk management, and spatial modeling in GIS frameworks (see section on Economic Optimization, Portfolio Theory, Spatial Analysis, and Risk Management, below).

At present, one major application of remote sensing is ecosystem and/or vegetation classification. Since the overarching goal is to protect biodiversity, having an accurate and efficient way to categorize forests (and thus ecosystems) is fundamental. Fortunately, the literature on this is extensive. The most promising references for this section are Brondizio and others (1996), Coulter and others (2000), Jorge and Blanco-Garcia (1997), Lawrence and others (1995), Lyon and others (1998), although others in the annotated bibliography below are useful as well. Our applications of the remote sensing and GIS technologies to ecosystem classification are not particularly novel in and of themselves. They are unique, however, in combination with the economic analyses and risk management to which we will link them. The literature on those steps is discussed next.

Economic Optimization, Portfolio Theory, Spatial Analysis, and Risk Management

This part of the project involves the tools, techniques, and principles that form the underpinnings of the analyses we will use. Again, each of these disciplines has a substantial literature associated with it, and we are adapting that literature to our purposes. The "Economic Model for a Land Use Portfolio" section above details many of the most important concepts and references some of the pertinent literature, but other concepts are discussed here.

One primary method of solving a problem of constrained optimization is through the use of linear programming (LP). The basics of LP are discussed in Murty (1983), Bazarra (1990), and many other texts. Research linking biological or ecological inputs with economics ones in an LP is common (see, for example, Paulsen and Wernstedt, 1995, and Taylor and others, 1992). However, this project would extend this application because of the novel objective function and constraints that grow out of the conservation concession approach. Further, the risk management perspectives and portfolio model of land use applied to private investment in conservation seems to be a rare combination.

Combining all of these within spatial analytical frameworks and a GIS involves further extensions of existing work, much of it done by the workers now with the USGS–CSP (see Bernknopf and others, 1997; Bernknopf and others, 1998; Pike and others, 1994). As noted above, spatial and statistical analysis of physical processes and their socioeconomic impacts is becoming more common. Griffith (1999), Fotheringham (2000), Ripley (1988), Cressie (1991), Pacione (1999), and others have completed texts, casebooks, and surveys of techniques that provide theoretical foundations for this project. Finally, this project will also use the more traditional analytical frameworks such as cost-benefit analysis (see

Boardman and others, 1996), dynamic optimization (Chiang, 1992), Bayesian statistics (Lee, 1989), and decision analysis under economic uncertainty (McKenna, 1986).

Biodiversity Classification and Prioritization

The purpose of this part of the project is to build upon the cost-effective information about forest structure and the spatial, economic, and statistical analysis methods from the above section. We will investigate the tools that our research partners are already using to measure biodiversity and prioritize certain ecosystems and parcels of forest for protection. Currently, there are indices based on biological or ecological metrics that assess how much biodiversity is present in an area. These indices might focus on species richness, degrees of rarity or endemism, genetic diversity, or numbers of higher order taxa contained in the area. The purpose of the USGS–CSP is not to rework these classification and prioritization systems—this is the domain of the research partners. Rather, we seek to understand the objectives that are being used, to formalize and operationalize their measurement, and to incorporate them into the analytical tools and risk management models we create.

The researchers from the Field Museum of Natural History have completed extensive biological inventories and ecological assessments on areas that CI has considered for inclusion into concession areas (see, for example, Alverson and others, 2000). In the study areas themselves, there are frequently government or private research institutions that study the ecology and structure of ecosystems as part of their internal planning and/or zoning processes. One example is the Iwokrama Center for Rainforest Conservation and Development (2000), which zoned different parts of the forests for timber, wilderness, tourism, villages, and so on. Wherever possible, we will use these types of analyses. Finally, there are general studies on biodiversity measurement and prioritization methods. Gaston (1996), Lawton and others (1998), and Spellerberg (1992) all investigate and/or develop systems for ranking areas in terms of their biodiversity and ecological importance. Smith (2000) compiled a large text that lists by category all the biodiversity research published in peer-reviewed literature.

Again, USGS–CSP's goal for this project is not to "improve" the measurement or prioritization methods used in protected areas creation and management, but to incorporate them into the spatial, risk, and economic optimization models that we are developing. By making these methods a part of the GIS, especially, we can provide a set of tools that can be used in the Bayesian management structure discussed above. This will allow for rapid updating of protected area status and ecosystem condition and facilitate better management decisions. Significantly, this integration of ecological priorities into GIS, risk, and economic models will be available to other conservation agencies that could use this method to formalize their own decision criteria.

Protected Areas and the Economics of Conservation

There is a large body of literature on protected areas creation and management in general, and on the need for and difficulty of attaining economic efficiency in conservation in particular. Examples of general work abound. Witting and Loesscheke (1993) explore whether the goal should be reserve optimization or minimization of species loss. Polasky (1998) investigates the problems in resolving private property rights with biodiversity conservation. Main and others (1999) assess the costs of conservation. Dreschler and Watzold (2001) model economic efficiency in allocation of biodiversity conservation funds between two areas. Kremen and others (2000) explored how effective different economic incentives at various scales were in achieving conservation. Ando and others (1998) demonstrate how cost-effectiveness of endangered species protection can be maximized across the United States by prioritizing habitat protection on the basis of land price. The historical and regional trends in biodiversity investment were investigated by Abromovitz (1991).

Also common is research directed to a method of protection, much of it conducted by our research partners. Gullison and Rice (2000) explored the prospect of marketing species conservation; Hardner and Rice (1999) analyzed forest concession policies to see how they might be used to increase and improve conservation. Bruner and others (2001) determined that parks were largely successful at protecting biodiversity, especially if adequate funding for policing was provided. Wong and Gullison (2000) surveyed catastrophic losses in protected areas and developed a system for risk assessment and management. Jackson and Gullison (2001) surveyed the budget size and composition of protected areas in various countries.

There are, of course, numerous other studies of protected areas in the regions in which our case studies will take place. However, our research has not yet progressed to that point. We have targeted the early work toward the remote sensing and data needs and gaining an understanding of the methods, needs, and structures of our research partners. The final section of this report is an annotated bibliography, which contains full reference for all of the works cited above. Other texts and papers are listed that are relevant, but were not specifically mentioned above.

ANNOTATED BIBLIOGRAPHY

Remote Sensing and Geographic Information Systems

Brondizio, Eduardo; Moran, Emilio; and Mausel, Paul, 1996, Land cover in the Amazon estuary: linking of the thematic mapper with botanical and historical data: Photogrammetric Engineering and Remote Sensing, v. 62, p. 921-929.

- The paper investigates whether 30-meter Landsat TM data might be able to do what the Landsat multispectral scanner (MSS) and the advanced very high resolution radiometer (AVHRR) could not: track post-deforestation processes and map land cover and land use classifications. The results indicate that the higher spatial and spectral resolutions make this a workable option that can achieve 81-100 percent accuracy. Fourteen classes were delineated, but global positioning system (GPS) test and training data were needed, and field observations were linked as well. The approach was adequate for identifying forests that were economically significant, and the results are clear enough to use in global carbon cycle modeling. The study site was a low-lying Brazilian floodplain forest.

Coulter, Lloyd; Stow, Douglas; and Hope, Allen, 2000, Comparison of high spatial resolution imagery for efficient generation of GIS vegetation layers: Photogrammetric Engineering and Remote Sensing, v. 66, no. 11, p. 1329-1335.

- The authors found that high-resolution digital orthophotoquads can be used to make GIS layers of the Southern California desert for vegetation classification with greater than 75 percent accuracy. They found that ground-tested information was about 10 percent better than that, but much more expensive. Key questions are whether or not this approach would work in the tropics, and to what degree the classification went. It may not be fine enough for our purposes.

Edwards, G., and Lowell, K.E., 1996, Modeling uncertainty in photointerpreted boundaries: Photogrammetric Engineering and Remote Sensing, v. 62, p. 377-391.

- This paper details a model for local boundary uncertainty estimation (fuzzy boundaries) that is fine enough to distinguish between separate stands of a forest. It includes two aspects of perception: discrimination and variability.

Eiumnoh, Apisit, and Shrestha, R.P., 2000, Improving vegetation classification in wet–dry forest ecosystems using DEM and Landsat TM: Photogrammetric Engineering and Remote Sensing, v. 66, no. 3, p. 318-327.

- The authors applied DEM and other ancillary remote sensing to Landsat TM images of wet-dry forests in Thailand to improve classification into land use and land cover maps. The results showed that classification accuracy can be improved from 65 percent up to 75 percent through the use of the added data. If the classification is supervised, this improves further to 84 percent.

Foody, Giles M., 1994, Ordinal-level classification of subpixel tropical forest cover: Photogrammetric Engineering and Remote Sensing, v. 60, p. 61-65.

- The conclusion of this paper was that it might be possible to predict subpixel ordinal classification of tropical forest cover with 75 percent accuracy, when using a four-group classification system. Using data from NOAA's AVHRR satellite data, with a typical spatial resolution of 1.1 km^2 pixels, the author developed a system that could fairly accurately sort areas smaller than that pixel size into categories of forest. Since AVHRR is the lowest resolution (and thus the lowest cost) remote sensing technology, being able to use it to target areas for further study with costlier methods could improve cost-effectiveness significantly.

Fuller, R.M., Groom, G.B., Mugisha, S., Ipulet, P., Pomeroy, D., Katende, A., Bailey, R., and Ogutu-Ohwayo, R., 1998, The integration of field survey and remote sensing for biodiversity assessment: a case study in the tropical forests and wetlands of Sango Bay, Bolivia: Biological Conservation, v. 86, p. 379-391.

Jorge, Luis Alberto and Blanco-Garcia, Gilberto Jose, 1997, A study of habitat fragmentation in southeastern Brazil using remote sensing and GIS: Forest Ecology and Management, v. 98, p. 35-47.

- This paper used remote sensing and GIS frameworks to evaluate the effects of habitat fragmentation. It measured edge effects, canopy changes, and other ecological effects in an attempt to demonstrate that these technologies can adequately track such changes. This is an approach that we could build on.

Keech, Maurice A., 1990, Remote sensing applied to ecological degradation: Chemistry and Industry, v. 9, p. 296-298.

Kimura, Hiroshi, and Yamaguchi, Yasushi, 2000, Detection of landslide areas using satellite radar inferometry: Photogrammetric Engineering and Remote Sensing, v. 66, p. 328-336.

- SAR was used to monitor the behavior of landslides that were otherwise missed by GPS. One of the goals of our project is to use the remote sensing data that are collected for verification to monitor natural changes in or around the protected areas. This study shows that at least one type and scale of remote sensing is appropriate for such a use. We will need to investigate others, and also investigate other natural changes.

Lambin, Eric F., 1996, Change detection at multiple temporal scales: Photogrammetric Engineering and Remote Sensing, v. 62, p. 931-938.

- The main point of this paper was that attempts using remote sensing to detect long-term changes over time in tropical forests that are remotely sensed often fail. This is because seasonal variation is much greater than annual or long-term changes, so that long-term changes are lost amid the noise of seasonal cycles. The authors use three West African landscapes to explore the effect of more frequent sampling and data aggregation. The idea is that aggregating data from many collections will smooth out the noise and give a truer picture of the long-term changes, if any. The paper is more centered on learning how to aggregate the data than on determining how often to resample. This is an important point to be aware of as we start looking for optimal remote sensing expenditure points.

Lawrence, William; Saatchi, Sasan; DeFries, Ruth; Dietz, James; Rice, Richard; Dietz, Lou Ann; Siguiera de Araujo, M.; and Alger, Keith, 1995, Utilization of SAR and optimal remote sensing data for habitat conservation in the tropical forest of Brazil: Proceedings of the International Geoscience Remote Sensing Symposium, v. 2, p. 1480-1482.

Lyon, J.G.; Yuan, Ding; and Lunetta, Ross S., 1998, A change detection experiment using vegetation indices: Photogrammetric Engineering and Remote Sensing, v. 64, p. 143-150.

- A test of seven different vegetation indices based on data from the Landsat multispectral sensor showed that the Normalized Green Vegetation Index was best at vegetation classification. The site was in Chiapas, Mexico. There was a history of significant disturbance in the area—fires, deforestation, reservoir construction, and some postclearing regrowth. At the very least, this paper gives a good explanation of seven vegetation indices that we should consider using for this project.

Myers, Norman, 1988, Tropical deforestation and remote sensing: Forest Ecology and Management, v. 23, p. 215-225.

- This older article is a good introduction to the fundamentals of remote sensing technology. It is especially good because it demonstrates early ideas about how remote sensing could be used to investigate tropical deforestation and ecosystem disruption. It is a good contrast to today's more highly technical papers and shows how far the technology has come in just 13 years.

Nagendra, Harini and Gadgil, Madhav, 1999, Biodiversity assessment at multiple scales: linking remotely sensed data with field information: Proceedings of the National Academy of Sciences of the USA, v. 96, no. 16, p. 9154-9158.

Riou, Robert and Seyler, Frederique, 1997, Texture analysis of tropical rain forest infrared satellite images: Photogrammetric Engineering and Remote Sensing, v. 63, p. 515-521.

Roy, P.S. and Tomar, Sanjay, 2000, Biodiversity characterization at landscape level using geospatial modeling technique: Biological Conservation, v. 95, no. 1, p. 95-109.

- The authors develop a method of characterizing GIS grid cells in an ecosystem in India. Patchiness, interspersion, juxtaposition, biological richness, digital elevation models, terrain complexity, disturbance index, and biodiversity value all come together to form the system. It could be useful to compare this with CI's system and others to see which might be best, easiest, and cheapest to use in our study areas.

Savitsky, Basil G., and Lacher, Thomas E., Jr., eds., 1998, GIS Methodologies for Developing Conservation Strategies: New York, N.Y., Columbia University Press.

- This book has a brief overview and three main sections. The first section is an introduction to the logic and terminology of digital mapping technologies, including GIS's, satellite image analysis, and global positioning systems. The second is a five-chapter set of examples of GIS applied to conservation in Costa Rica. The third is a six-chapter case study of Gap Analysis as used in a USAID project. The early parts of the book are useful in outlining the basics of remote sensing and GIS, and the case studies are useful and lucid illustrations of how the technology is used to build models, plan and prioritize conservation strategies, and assist in decisionmaking.

Skole, D., Chomentowski, W.H., and Salas, W.A., 1994, Physical and human dimensions of deforestation in Amazonia: BioScience, v. 44, p. 314-322.

Sohn, Y., Moran, E., and Gurri, F., 1999, Deforestation in north-central Yucatan: Mapping secondary succession of forest and agricultural land use in Sotuta using the cosine of the angle concept: Photogrammetric Engineering and Remote Sensing, v. 65, no. 8, p. 947-958.

Stone, Thomas; Schlesinger, Peter; and Houghton, Richard, 1994, A map of the vegetation of South America based on satellite imagery: Photogrammetric Engineering and Remote Sensing, v. 60, p. 541-551.

- The authors developed a digital vegetation map of the entire continent of South America at 1-km resolution. We obviously need finer resolution, but it's a good start on continental-scale vegetation delineation.

Stoms, David, 1992, Effects of habitat map generalization: Photogrammetric Engineering and Remote Sensing, v. 58, p. 1587-1591.

- This paper investigates how the scale of GIS information affects decisions about biodiversity measurement and prioritization. A case study in the southern Sierra Nevada in California measured the extent to which decreasing loss of scale "blurred out" smaller habitat parcels and altered the ensuing measurements of species richness. This is an extremely relevant concept for our project, because part of what we will try to do is optimize the amount and scale of remote sensing and GIS information that conservation groups need to purchase. We also need to investigate how tropical forests differ from temperate mountain forests.

Todd, Stella, and Hoffer, Roger, 1998, Responses of spectral indices to variations in vegetation cover and soil background: Photogrammetric Engineering and Remote Sensing, v. 64, no. 9, p. 915-921.

- This paper evaluates vegetation cover and the soil background's effects on the green vegetation index (GVI) and on the normalized green vegetation index (NGVI), as imaged by the Landsat TM. The results showed that GVI was more accurate than NGVI and less dependent on existing knowledge about soil background moisture. It may or may not be useful to our work to use one of these indices instead of developing our own.

Trietz, Paul, and Howarth, Philip, 2000, Integrating spectral, spatial, and terrain variables for forest ecosystem classification: Photogrammetric Engineering and Remote Sensing, v. 66, no. 3, p. 305-317.

- The authors used information from the compact airborne spectrographic imager (CASI) to classify boreal forests with low to moderate relief. By using spectral, spectral-spatial, and terrain variables, they significantly improved the classification, showing that large gains are possible by effectively bundling information in this way.

Verbyla, D.L. and Richardson, C.A., 1996, Remote sensing clearcut areas within a forested watershed: comparing SPOT HRV panchromatic, SPOT HRV multispectral and Landsat thematic mapper data: Journal of Soil and Water Conservation, v. 51, no. 5, p. 423-427.

- This article explores the ability of three remote sensing types (SPOT HRV panchromatic, SPOT HRV multispectral, and Landsat TM) to detect clearcut areas by identifying exposed soil and distinguishing it from nonexposed soil. The three types were very close to each other, with only the SPOT panchromatic being slightly less accurate. All were comparable with aerial photographs at 1:15,840 scale. The mean accuracy was 85 percent; omission error rates were < 5 percent, and commission errors were between 2 and 37 percent. Since conservation concessions require verification that forests have been maintained before payments are made, CI will likely use something similar to this paper's method. This presents an opportunity to use those remote sensing images to detect other changes in and around the forest for use in managing the protected areas.

Economic Optimization, Portfolio Theory, Spatial Analysis, and Risk Management

Bazarra, M.S.; Jarvis, J.J.; Sherali, H.D., 1990, Linear programming and network flows: New York, NY, John Wiley and Sons, Inc.

Bernknopf, R.L., and Karl, Herman, 1998, Thoughts on the application of science to decisionmaking under uncertainty: the nexus between science and policy: Water Resources Update, v. 114, p. 14-20.

Bernknopf, R.L.; Brookshire, D.S.; McKee, M.; and Soller, D.R., 1997, Estimating the social value of geologic map information: a regulatory application: Journal of Environmental Economics and Management, v. 32, p. 204-218.

Bernknopf, R.L.; Campbell, R.H.; Brookshire, D.S.; and Shapiro, C.D., 1998, A probabilistic approach to landslide hazard mapping in Cincinnati, Ohio, with applications for economic evaluation: Bulletin of the Association of Engineering Geologists, v. 25, p. 39-56.

Boardman, A.E.; Greenberg, D.H.; Vining, A.R.; and Wiemer, D.L., 1996, Cost-benefit analysis—concepts and practice: Upper Saddle River, NJ, Prentice-Hall, Inc.

Chiang, Alpha C., 1992, Elements of Dynamic Optimization: New York, NY, McGraw-Hill, Inc.

Cressie, Noel C., 1991, Statistics for Spatial Analysis: New York, NY, J. Wiley Inc.

Dixon, J.B. and Sherman, P.B., 1990, Economics of protected areas: a new look at benefits and costs: Washington, D.C., Island Press.

Fotheringham, A.S., 2000, Quantitative geography: perspectives on spatial data analysis: London, SAGE Publications.

Fotheringham, A.S., and Wegener, Michael, eds., 2000, Spatial models and GIS: new potential and new models: London, Taylor and Francis Publications.

Griffith, Daniel A., 1999, A casebook for spatial statistical analysis: a compilation of analyses of different thematic data sets, London and New York, Oxford University Press.

Kunreuther, H.; Platt, R.; Bernknopf, R.L.; Buckley, M.; Burkett, V.; Conrad, D.; Davison, T.; Deutsch, K.; Geis, D.; Good, J.; Jannereth M.; Knap, A.; Lane, H.; Ljung, G.; Mcauley, M.; Mileti, D.; Miller, T.; Morrow, B.; Myers, J.; Pielke, R.; Pratt, A.; and Tripp, J., 1999, The hidden cost of coastal hazards: implications for risk assessment and mitigation: The John Heinz Center for Science, Economics and Environmental Policy, Island Press.

Lee, Peter M., 1989, Bayesian statistics: an introduction: New York, NY, Oxford University Press.

Lewis, Tracy, and Nickerson, David, 1989, Self-insurance against natural disasters: Journal of Environmental Economics and Management, v. 16, p. 202-223.

Lind, R.C., 1973, Spatial equilibrium, the theory of rents, and the measurement of benefits from public programs: The Quarterly Journal of Economics, v. 87, p.188-207.

McKenna, C.J., 1986, The Economics of Uncertainty: Sussex, U.K., Harvester Press Publishing Group.

This slim textbook contains a useful primer on decisionmaking under uncertainty, expected utility theory, consumption and savings under uncertainty, and an introduction to portfolio theory. It is not heavily mathematical, yet is a valuable introduction and/or review of fundamentals of risk-based economic analysis.

Murty, Katta G., 1983, Linear programming: New York, NY, John Wiley and Sons, Inc.

Pacione, Michael, 1999, Applied geography principles and practice: an introduction to useful research in physical, environmental and human geography: London, Routeledge Press.

Paulsen, Charles M., and Wernstedt, Kris, 1995, Cost-effectiveness analysis for complex managed hydrosystems: an application to the Columbia River basin: Journal of Environmental Economics and Management, v. 28, p. 388-400.

- The authors link a salmon population simulation model with a linear program-based optimization model to determine a cost-effective set of hydrosystem management actions that would allow recovery of salmon stocks in the Columbia River.

Pike, R.J.; Bernknopf, R.L.; Tinsley, J.C. III; and Mark, R.K., 1994, Hazard of earthquake-induced lateral-spread ground failure on the central California coast modeled for earth science map data in a geographic information system: U.S. Geological Survey Open-File Report 94-662.

Proceedings from the Second International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences, 2000, Quantifying spatial uncertainty in natural resources: theory and applications for GIS and remote sensing: Chelsea, Mich., Ann Arbor Press.

Quiggen, John, 1992, Risk, self-protection and ex ante economic value: some positive results: Journal of Environmental Economics and Management, v. 23, p. 40-53.

Ripley, B.D., 1988, Statistical inference for spatial processes: Cambridge, U.K., Cambridge University Press.

Shogren, J.F. and Crocker, T.D., 1991, Risk, self-protection and ex ante economic value: Journal of Environmental Economics and Management, v. 20, p.1-15.

Sinn, Hans-Werner, 1983, Economic decisions under uncertainty: Amsterdam, North-Holland Press.

Taylor, M.L.; Adams, R.M.; and Miller, S.F., 1992, Farm-level response to agricultural effluent control strategies: the case of the Willamette Valley: Journal of Agricultural and Resource Economics, v. 17, no. 1, p. 173-185.

This paper links an agricultural production simulation model with a linear program to predict farm-level responses to various policies designed to control runoff. The Erosion-Productivity Impact Calculator (EPIC) was used to simulate the agricultural production, erosion, and effluent that could result from various responses to the policies above. A linear program was then run using the General Algebraic Modeling System (GAMS) to simulate the set of practices that would be taken by farmers seeking to maximize profit under the constraints of the various policies.

Biodiversity Classification and Prioritization

Alverson, W.S., Moskovits, D.K., and Shopland, J.M., eds., 2000, Bolivia-Pando, Rio Tahuamanu—Rapid biological inventories report 1: Chicago, Ill., The Field Museum.

Blockhus, J.M., Dillenbeck, M.R., Sayer, J.A., and Wegge, Per, eds., 1992, Conserving biological diversity in managed tropical forests: Gland, Switzerland and Cambridge, U.K., The International Union for Conservation of Nature and Natural Resources–World Conservation Fund.

- The 1990 meetings of the International Tropical Timber Organization (ITTO) resulted in a resolution that all tropical timber should be harvested from sustainably managed forests by 2000. This text examines the legal and practical obstacles and methods that such a project entails. Though our project does not attempt to manage a sustainable timber harvest—in fact, it appears as an alternative solution to the failures of such efforts—it might be useful to investigate where and how sustainable forestry fails to that those pitfalls can be avoided. This document also contains much information that will be useful in our case studies. A chapter for each country outlines its biodiversity, the extent and security of productive forests, classifications of soil and forest types, and logging practices and rates.

Gaston, K.J., ed., 1996, Biodiversity: a biology of numbers and difference, Oxford, U.K., Blackwell Press.

Iwokrama Center for Rainforest Conservation and Development, 2000, Zoning of the Iwokrama forest—working paper: Georgetown, Guyana.

- The Iwokrama Forest in Central Guyana is located near the study area where a conservation concession is being established. This paper documents the division of the forest into a sustainable utilization area and a designated conservation area. It tracks the biophysical and ecological variables that are relevant in Iwokrama and likely to be factors in the concession area as well. It also analyzes the socioeconomic issues and identifies stakeholders that are critical to successful protected areas. Together, the patterns seen in physical and social data will be most useful in the first case study our project will analyze. We are currently corresponding with the authors to determine what GIS and remote sensing information they had, and what additional information they would have benefited from having.

Lawton, J.H.; Bignell, D.E.; Bolton, B.; Bloemers, G.F.; Egglteon, P.; Hammond, P.M.; Hodda, M.; Holt, R.D.; Larsen, T.B.; Mawdsley, N.A.; Stork, N.E.; Srivastava, D.S.; Watt, A.D., 1998, Biodiversity inventories, indicator taxa, and effects of habitat modification in tropical forest: Nature, v. 391, p. 72-76.

Ramdass, I., and Hoosein, M., 1999, Vital in-situ and ex-situ sites for flora and fauna management in Guyana: Georgetown, Guyana.

Smith, Charles M., 2000, Biodiversity studies: a bibliographic review: Lanham, M.D., and London, Scarecrow Press, Inc.

Spellerberg, Ian F., 1992, Evaluation and assessment for conservation: London, U.K., Chapman and Hall.

- This book describes a thorough system for measuring, assessing, valuing, prioritizing, and protecting biodiversity and ecosystems. Again, our research partners have their own methods for doing many of those things, and the purpose of this project is not to replace those systems, but optimizing any system requires knowing what the alternatives are. This book presents an extremely detailed approach to all ecological facets of biodiversity conservation and is useful for background knowledge on the issues.

Zagt, R., and ter Steege, H., 1999, Tree diversity in Guyana: critical forest regions for the establishment of a protected areas system: Tropenbos-Guyana Programme/ Utrecht University.

Protected Areas and the Economics of Conservation

Abromovitz, J.N., 1991, Investing in biological diversity: U.S. research and conservation efforts in developing countries: New York, NY, World Resources Institute.

- This book reports the results of a 1990 survey that sought to measure the amount, source, and types of investments in international biodiversity and conservation. It identifies major patterns in private and U.S. Government investment in various regions of the globe. It also breaks down how much of an average conservation dollar went to research, site management, policy planning, education, and so on. These patterns are now 10 years old, but they still provide a useful metric for assessing the cost-effectiveness of today's conservation investments and strategies.

Ando, Amy; Camm, Jeffrey; Polasky, Stephen; and Solow, Andrew, 1998, Species Distributions, Land values, and efficient conservation: Science, v. 279, p. 2126-2128.

- The authors use county-level data on land prices and incidence of endangered species to assess the cost effectiveness of protecting endangered species. By considering heterogeneity in land prices and the concomitant changes in the cost of setting aside land for endangered species habitat, they show that substantial efficiency gains can be made either in the cost of covering a certain number of species, or in maximizing the coverage allowed by a fixed budget.

Attwell, C.A.M., and Cotterill, F.P.D., 2000, Postmodernism and African conservation science: Biodiversity and Conservation, v. 9, p. 559-577.

Bonnie, Robert; Schwartzmann, Stephan; Oppenhiemer, Michael; and Bloomfield, Janine, 2000, Counting the cost of deforestation: Science, v. 288, p. 1763-1764.

Bruner, A.G.; Gullison, R.E.; Rice, R.E.; and de Fonseca, G.A.B., 2001, Effectiveness of parks in protecting tropical forest biodiversity: Science, v. 291, p. 125-128.

- The authors investigated threats to protected areas from human impacts in 93 protected areas in 22 countries. They found that parks are largely successful in preventing land clearing, fire, unauthorized hunting, and grazing. Basic park management activities, especially when combined with compensation to local communities, contribute to large increases in effectiveness.

Dreschler, Martin, and Watzold, Frank, 2001, The importance of economic costs in the development of guidelines for spatial conservation management: Biological Conservation, v. 97, p. 51-59.

- This paper investigates biodiversity-enhancing land use to see which spatial allocations of subsidies for this purpose might increase efficiency. The authors build a two-area economic model to determine the optimal allocation of resources between the areas and show that, as marginal costs of conservation increase, allocations approaching equal between the two areas become more efficient.

Gullison, R.E.; Rice, R.E.; Blundel, A.G., 2000, Marketing species' conservation: Nature, v. 404, p. 923-924.

Hardner, J.J., and Rice, R.E., 1999, Rethinking forest concession policies *in* Keipi, K., ed., Forest Resource Policy in Latin America: Washington, D.C., Johns Hopkins Press.

Hardner, J.J., and Rice, R.E., 1994, Financial constraints to 'sustainable' selective harvesting of forests in the eastern Amazon: bioeconomic modeling of a forest stand in the State of Para, Brazil, *in* Proceedings of Reforma de las Politicas de Gobierno Relacionadas con los Recursos Forestales en America Latina: United States Agency for International Development, The World Bank, and the Center for International Forestry Research.

Jackson, Siobahn, 2001, A review of protected areas budgets in developing countries: Washington, D.C., Center for Applied Biodiversity Science–Conservation International Report.

- This report is part of a set of reports to CI–CABS intended to improve implementation of conservation concessions and other protected areas. In it, the various cost sources and structures involved in creating and managing protected areas were analyzed and organized into a systematic framework. Rough estimates of operating budgets were derived from surveys of protected areas around the globe.

Katzmann, M.T., and Cale, W.G., Jr., 1990, Tropical forest preservation using economic incentives: Bioscience, v. 40, p. 827-832.

Kremen, K.; Niles, J.O.; Dalton M.G.; Daily, G.C.; Ehrlich, P.R.; Fay, J.P.; Grewal, D.; and Guillery, R.P., 2000, Economic incentives for rain forest conservation across scales: Science, v. 288, p. 1828-1832.

Main, M.; Roka, F.; and Noss, R., 1999, Evaluating costs of conservation: Conservation Biology, v. 13, p. 1262-72.

Montgomery, C.A., and Brown, G.M., Jr., 1992, Economics of species preservation: the spotted owl case: Contemporary Policy Issues, v. 10, p. 1-12.

- This paper attempts to derive the supply curve for—and thus the marginal cost of—protection of the endangered species, the Northern Spotted Owl. By using expert knowledge and a population dynamics simulation model, the authors quantitatively related species survival to habitat availability. Then, they calculated the opportunity cost of not cutting timber in areas where owl habitat either is or potentially could be. They used an econometric model of stumpage and wood products to derive this value. The result is a supply curve that traces the relationship of probability of continued owl survival as a function of foregone timber revenue and the ensuing producer and consumer surplus.

Polasky, Stephen, 1998, When the truth hurts: endangered species policy on private land with imperfect information: Journal of Environmental Economics and Management, v. 35, p. 22-47.

Witting, Lars, and Loesschcke, Volker, 1993, Biodiversity conservation: reserve optimization or loss minimization?: Trends in Ecology and Evolution, v. 8, no. 11, p. 417.

Wong, Carmen, and Gullison, R. E., 2000, Risk assessment and management of catastrophic threats to tropical protected areas: Washington, D.C., Center for Applied Biodiversity Research–Conservation International Report

- This paper is a compilation of 64 catastrophic events, both natural and anthropogenic, that took place in 32 protected areas around the planet. The authors identified trigger events to catastrophic loss and the conditions that increased the areas' susceptibility to these events. They also describe a three-step process for risk management that includes assessing risks, establishing "comfort levels" with various threats, and monitoring one or more indicators for the trigger events that bring about the dramatic losses.