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DETERMINING SUSTAINABILITY INDICATORS BY REMOTE SENSING

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ABSTRACT:
Sustainable development is that which meets the needs of the present without foreclosing the needs or options of the future. There is often a time lag between a development and its negative environmental impacts. As well, the impacts of developments on the environment may be difficult to evaluate over a limited period. Early warning indicators need to be developed that identify and monitor impacts before excessive damage on the environment occurs. These indicators should account for ecological, economic and environmental dimensions of development, and should aid the assessment of the effectiveness of policies designed to protect the environment. Environmental indicators derived from remote sensing technologies should enable the mapping, monitoring and determination of the status and condition of natural and managed ecosystems in order to provide timely information to identify environments at risk. They should improve environmental decision making by contributing to the implementation of sustainable development practices through more informed environmental management. They require an inter-disciplinary approach, involving inputs from specialists on the physical environment with those involved in socio-politico-economic environments, to indicate landscapes and ecosystems at risk, and to provide information for management decisions related to sustainable development practices.

1. INTRODUCTION

Only in the last few decades have we recognised the extent to which humans can modify and alter the energy and mass exchanges that occur between atmosphere, oceans and biota, and understood that the changes being wrought may be beyond the resilience of natural systems to absorb. While we marvel at the diversity of the Earth's environments, we have little knowledge of the functioning and interaction of these environments at a global scale. As well, we do not have precise information on the location, extent and impact of the human modifications that are taking place. There is general agreement among scientists that unravelling the processes involved in the functioning of the Earth system, together with identifying the forces acting to promote global change, as well as determining the rate of that change, requires the availability of sets of compatible, homogeneous global data for a variety of key terrestrial variables. Systems have been planned and/or launched to measure remotely many variables associated with global change**.** The development of GEOSS (Global Earth Observation System of Systems) should be an important contribution to this need. Such studies require a multi-disciplinary study by many scientists.

2. SUSTAINABLE DEVELOPMENT

Sustainable development refers to the adoption of practices in relation to environmental use and management which provide a satisfactory standard of living for today's population and which do not impair the capacity of the environment to provide for and support the needs of future generations. The concept of sustainability in respect of the use of environment resources includes the notion that the outputs derived, whether they are from land, water or air can be produced continuously over time, and that a balance can be achieved between the rate of economic growth, their use and environmental quality, that minimises the risk of long term degradation. It is argued that through careful management and the use of appropriate practices, the long-term viability of the environment can be maintained. A sustainable development practice is one which is sensitive to ecological constraints and seeks to minimise the undesirable effects of exploitation and use which might impact negatively on the longer-term viability of a resource. It is also one in which the full economic and environmental replacement costs associated with the use of a resource should be met.

Sustainable development cannot be divorced from issues of equity, welfare, lifestyle and the expectation of improved standards of living in most countries. Nor can the implementation of sustainable development practices be separated from the economic and political structures that exist within and between countries. The Principles of the 1992 Rio Declaration, which were reaffirmed at the 2002 Johannesburg World Summit on Sustainable Development, define the roles of the stakeholders in the sustainable development, and rights and responsibilities in development processes. The Johannesburg declaration went on to refer to: '…the three components of sustainable development, economic development, social development and environmental protection as interdependent and mutually reinforcing pillars. Poverty eradication, changing unsustainable patterns of production and consumption, and protecting and managing the natural resource base of economic and social development are overarching objectives of, and essential requirements for, sustainable development'.

The recommendations of the draft Johannesburg Declaration for sustainable development included statements on conservation and management of resources by:

- planning and management of land resources,
- combating deforestation and conservation of bio-diversity,
- combating desertification and drought,
- protection of the quality and supply of fresh water,
- protection of the oceans and coastal areas,
- rational use and development of their living resources
- protection of the atmosphere from pollution
- the management of natural disasters

Many models of development are based purely on economic measures, which emphasize the economics of development, with little concern for natural resources. According to Daly (2000) sustainable development must take into account the ecological, economic and social components of development. His model of an economy is based on 'ecological economics', in which the economy grows by transforming its environment from natural capital into man-made capital. Optimal growth occurs when the marginal cost of natural capital transformation is equal to the marginal benefits to mankind. In this scenario, there is a limit to the natural capital and therefore expansion of an economy is stringently limited. This provides a measure of sustainability. Sustainable development can be defined in terms of the available natural capital. If the transformation of natural capital to man-made capital is above the optimal level, then the development can be interpreted as unsustainable.

Sociological factors are also important in assessing sustainability of development. These factors are concerned with why things happen, rather where they happen (Rindfuss et al 1998). Knowledge of the relationship between human activity and development is essential to understanding the reasons and impact of the development, and hence contributing to its sustainability.

Kates (2000) has reviewed the relationship between population and consumption in terms of the formula I=PxC, where I = environmental degradation and/or resource depletion, P = the number of people or households and C = the transformation of energy, materials and information. The simple formula shows that as population increases, resource depletion also increases. In addition, in terms of Daly's model above, the value of C must be controlled by the optimal level of transformation of natural capital. Therefore, as population increases, since natural capital available for transformation effectively remains constant, there will be even less natural resources available per capita. The maintenance of sustainability therefore becomes even more difficult and yet more critical.

The large scale implementation of sustainable development practices is unlikely to occur or be successful without accompanying economic, social and political change. Governments have to institute policies that encourage the implementation of production methods that operate within ecological limits and which lead to different patterns of resource consumption than currently exist. Policies should favour innovation and technological change which offer resource efficient solutions and what Clayton et al (1996) call progressive adjustments, with emphasis on system level sustainability at the national level, and project sustainability at the local level. They also advocate using the "precautionary principle" which assumes that all natural systems are vulnerable thereby demanding that adequate risk evaluation be part of any development process. Lambin at al (1999) in the LUCC (Land Use and Land-Cover Change) Implementation Strategy have stated that humans are unlikely to change their behaviour unless they see the benefits. This is clearly the challenge of transition to a sustainable world.

3. SUSTAINABILITY INDICATORS

The determination of sustainability of development is complex and not clearly defined. In addition, there may be a time lag between development and its negative impact. The concept of sustainability indicators has been developed to monitor progress and assess the effectiveness and impact of policies on natural resource development (Rao 1998). Becker (1997) has described the approaches that can be taken for assessing sustainability as 'exact measurement of single factors and their combination into meaningful parameters' and 'indicators as an expression of complex situations', where an indicator is 'a variable that compresses information concerning a relatively complex process, trend or state into a more readily understandable form' (Harrington et al 1993). A term that is also used in relation to the measure of sustainability of a region, usually a country, is Environmental Sustainability Index (ESI), which 'measures the progress toward environmental sustainability of 142 countries.' (Yale Center for Environmental Law and Policy, 2002). ESI are large scale measures of the environmental performance, which are not measurable by remote sensing. ESI is therefore not relevant to this paper. The (NRTEE 2003) recommends that, in addition to the GDP and other popular economic indicators, the Government of Canada should report annually a small set of indicators illustrating key aspects of natural, human and, eventually, social capital. To start with, the following indicators should be used: Natural capital; including air quality trend indicator, freshwater quality indicator, greenhouse gas emissions indicator, forest cover indicator, and extent of wetlands indicator; and human capital, educational attainment. Several of these indicators may be assessed by remote sensing, and are similar to aspects referred to later in this paper. Similar indicators have been suggested by Alliance for a Sustainable Atlanta (1999) and a number of other countries.

Becker (1997) has listed sustainability indicators under the headings of Economic, Environmental, Social and Composite. Environmental indicators for agriculture include such items as *yield trends, coefficients for limited resources, material and energy flows and balances, soil health, modeling and bioindicators*. Indicators used in practice are usually application specific, but are expected to be unbiased, sensitive to changes, and convenient to communicate and collect. Dumanski (1997) has described a land quality indicator for assessing sustainable land management, which includes *nutrient balance, yield trend and variability, land use diversity and land cover*, which are relevant to short term studies. These indicators should be complemented by other indicators related to economic viability, system resilience, and social equality and acceptability.

Berroterán (1997) has suggested the following criteria for assessing sustainable agriculture: *environmental and technological criteria* such as agro-diversity, soil degradation and water use, land availability and use, crop yield, energy efficiency and fertilizer use; *economic criteria* such as cost-benefit ratio and import and expert ratios; and *social criteria* such as availability of food and sustenance per capita. From the indicators, a 'sustainability index' was determined that led to the conclusions on the sustainability of a particular agricultural practice. Gameda at al (1997) referred to the Framework for Evaluation of Sustainable Land Management (FESLM), which aims to determine the environmental, economic and social sustainability of farming systems, based on a case study in Canada. There are five categories of indicators under the headings of *Productivity, Security, Protection, Viability and Acceptability*. Those given under *Productivity* are *soil fertility, crop productivity, and crop resilience*. Driessen (1997) has stated that a land-use system is 'biological sustainable if essential attributes of a land unit do not deteriorate to the extent that intervention is required'.

The objectives and scope of the LUCC (Lambin et al. 1999), which is a core project of IGBP (International Geosphere-Biosphere Programme) and IHDP (International Human Dimensions Programme On Global Environmental Change) are broadly described as: assessing the patterns and processes of land-cover change; determining human responses to land-use and land-cover change; developing integrated global and regional models; and developing databases on land surface, biophysical processes and their drivers. The strategy has three foci, of which Focus 2: Land-cover Changes is the most relevant to this paper. It states as follows:

'To measure land-cover change by remote sensing, one needs:
(i) biophysical indicators strongly related to land-cover conditions which can be measured by remote sensing;
(ii) a reference state for the land-cover at every location as a standard against which to compare current situations;
(iii) a technique of detecting changes. Land-cover change analysis requires the measurement of a set of indicators of the biophysical attributes of the surface, the seasonality of these attributes and their fine scale spatial pattern.'

Lambin et al. (1999) describe the need to define both direct and indirect indicators that describe various aspects of land-cover change. For LUCC, direct indicators describe the physical environment, whereas indirect indicators describe secondary interactions or consequences that occur in adjoining systems. While appropriate indicators have yet to be determined, those relevant to LUCC should firstly describe the characteristics and types of land cover, and secondly land quality.

Becker (1997) has discussed the implementation of sustainability indicators in terms of time and space. Many indicators, including some of those mentioned above do not cover adequate time spans to demonstrate intergenerational changes, which is the principal criterion of sustainability. The criteria for the selection of Sustainability Indicators, as recommended by Becker, and compiled with reference to the work of a number of scientists, are given in Table 1. The complexity of defining sustainability indicators is revealed by these sets of criteria.

4. APPLICATION OF REMOTE SENSING SUSTAINABLE DEVELOPMENT

The application of remote sensing for defining sustainability indicators is not well developed, but remote sensing has the potential for providing important inputs to sustainability studies. Put briefly, it is necessary to identify those indicators that can be measured reliably by remote sensing on a regular basis, are reproducible, without bias and truly reflect the characteristics of the environment when it is changing. Appropriate indicators must be determined in association with experts in the particular fields in which the indicators are being developed.

Table 1 Criteria for the Selection of Sustainability Indicators (after Becker 1997)

Scientific Quality	Ecosystem relevance	Data Management	Sustainability Paradigm
• Indicator really measures what it is supposed to detect • Indicator measures significant aspect • Problem specific • Distinguishes between causes and effects • Can be reproduced and repeated over time • Uncorrelated, independent • Unambiguous	• Changes as the system moves away from equilibrium • Distinguishes agro-systems moving away from sustainability • Identifies key factors leading to unsustainability • Warning of irreversible processes • Proactive in forecasting future trends • Covers full cycles through time • Corresponds to aggregation level • Highlights links to other system levels • Permits tradeoff detection and assessment between system components and levels • Can be related to other indicators	• Easy to measure • Easy to document • Easy to interpret • Cost effective • Data available • Comparable across borders over time • Quantifiable • Representative • Transparent • Geographically relevant • Relevant to users • User friendly • Widely accepted	• What is to be sustainable? • Resource efficient • Carry capacity • Health protection • Target values • Time horizon • Social welfare • Equity • Participatory definition • Adequate rating of single aspects

There have been many examples of papers given on the general topic of the application of remote sensing for sustainable development. They have generally covered examples of image products available for assessing sustainable development, remote sensing techniques for extracting relevant information about the environment, and case studies in which characteristics of the environment have been derived and assessed in terms of the sustainability of a particular form of development. A good example is that of Rao (1998), which describes the so-called Integrated Mission for Sustainable Development (IMSD) in India. In this case-study, three types of data were collected in the study area: satellite image data, collateral data and socio-economic data. A resource database describing all aspects of the terrain surface, integrated into a GIS was then formed to provide a set of decision rules for assessing sustainable development, leading to an action plan. In this case appropriate indicators were apparently determined to suit the application.

Table 1 refers primarily to the selection of indicators. Once they have been defined, the method of determining them, including the role that remote sensing will play, can be ascertained. A number of the indicators quoted above for assessing the sustainability of agriculture for example, can be assessed by remote sensing and incorporated into GIS as an enabling technology. Likewise, other aspects of the environment, such forest management, afforestation, reforestation and deforestation (ARD), can be assessed in terms of appropriately defined indicators (Imhoff et al 1999).

The reproducibility of measurements from remote sensing data must be proven, since many aspects of remote sensing are still considered as experimental rather than operational. Therefore remote sensing experts will need to be able to calibrate and validate their measurements used for determining sustainability indicators by remote sensing. This is an issue being addressed by CEOS Working Group on Calibration and Validation (WGCV) as well as ISPRS WG I/2. It is a significant issue requiring attention by remote sensing experts using a range of sensors.

From the point of view of technologies based on current satellite sensors, remote sensing can input spatial and temporal information into both physical processes and socio-economic models. The following discussion seeks to demonstrate the positive contribution remote sensing can make to a range of sustainability indicators.

- vegetation degradation and clearance - this is typically manifest by a reduction in biomass and changes in cover type. A number of optical sensors using vegetation indices and change detection techniques permit the mapping, monitoring and measurement of the areal extent of the change.

- forest disturbance - small and relatively subtle changes to the forest canopy caused by processes such as selective logging, fuel wood collection, treefall and windthrow may be detectable through changes in biomass, as well as by measures related to forest texture all of which can be determined from radar, such as multi-frequency and polarimetry systems;

- biodiversity - the species composition of a forest, which influences its spectral response, as well as patterns of clearance, have the potential to provide generalised indicators of biodiversity, that may be used to aid conservation practices as well as sustainable timber harvesting policies. Also radar is sensitive to structural variations in surface materials and has proved useful in differentiating between habitat types

- land cover change, the greatest threat to biodiversity and a major variable in the loss of nutrients from productive lands; land cover may be mapped and monitored by a range of remote sensing data sources, including optical and radar; this requires development of techniques to spectrally unmix the class composition of mixed pixels to capture land cover modifications systematically and on a repetitive basis;

- agricultural crop estimation, involves the application of appropriate hyperspectral vegetation indices derived from the regular and systematic data capture over agricultural regions, and when combined with agro-meteorological data, can provide daily, weekly and annual information on crop condition and status; this data can also be used to generate yield estimates and comparisons of annual production trends

- soil condition and erosion - vegetation disturbances and agricultural management practices influence the susceptibility for soil erosion; direct and indirect indicators of this potential may be derived through spectral characterisation of the soil (if exposed) or of vegetation conditions (if covered); changes of the soil surface composition over time are indicators of land degradation, salinity and erosion;

- inland water quality and coastal wetland condition - agriculture, fish productivity, human consumption are all highly dependent on the availability and quality of the aquatic environment; hyperspectral remote sensing data and synthetic radar data may be used to analyze these indicators;

- potential for landslides - within forest catchments, landslides are a major source of sediment, with the slipped land highly erodable for a considerable period after the initial movement; with major cover changes being mapped from optical data with volume estimates, height displacement and flood level measurements are best obtained from interferometric radar

- drought stress is commonly marked by abrupt changes in land cover and vegetation condition as encountered in rainforest drying out and exacerbated long term by phenomena such as the El Nino; it strongly influences the curing rate and fire potential of a forest; hyperspectral indicators of the canopy moisture content detected by remote sensing may reveal the spatial distribution of drought impacts that can help plan the human use of fire to minimise the potential for catastrophic damage.

- local, regional and global changes in surface temperature; variations in rainfall distribution and variability; increases in atmospheric aerosols; declining extent of snow and ice cover and enhanced greenhouse gas emissions all are now routinely monitored and measured by Earth satellites, providing information for planning and implementing sustainable development practices.

- disaster management - indicators for natural disaster management can be identified and characterised from the interaction of the environmental components involved in any natural disaster event. This information can then be input into physical process models and married with data that incorporates the behaviours, outcomes and experiences from previous similar events in order to provide the basis for defining the degree of risk and vulnerability and for designing and implementing appropriate disaster reduction and response measures.

The information derived from remote sensing can be directly related to measuring important socio-economic impacts. Rates of land cover change and drought, for example, will strongly influence vegetation yield, which substantially impact upon human health and well-being. They will for example, influence the demand for and rate of fertiliser application, which may be associated with downstream pollution. Issues such as soil erosion are a major concern for land users, but also are strongly associated with major consequential impacts, including the silting of lakes and damage to hydroelectric power stations.

Remote sensing and GIS are important tools for the management of sustainable development. However, defining sustainability indicators and understanding their application in assessing and monitoring sustainable development is a multi-disciplinary activity, involving experts in remote sensing, as well as those in ecology, biology, sociology, human resources and politics. Close cooperation with such a team of experts will be essential in these studies in future.

6. CONCLUSIONS

The purpose of this paper is to present some principles for assessing sustainability of development, and to describe the ways in which remote sensing can be used in this process. Definitions of sustainable development have been given and the approach to its assessment based on sustainability indicators described. While a number of indicators are currently available, there appears to be no consensus on the most appropriate indicators for a particular application.

The application of remote sensing and as a tool for assessing sustainable development must be related to the sustainability indicators that can be measured with the technology. An attempt has been made in this paper to describe some of the indicators that are measurable with remote sensing. While remote sensing will not be the only tools for assessing these indicators, they should make an important contribution to this multi-disciplinary process, provided they satisfy scientific criteria, such as being subject to strict calibration and validation. A great deal has yet to learnt about these processes and how the full potential of remote sensing can be achieved in this very important issue of sustainable development.

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