

REMOTE SENSING FOR ASSESSING ENVIRONMENTAL IMPACTS BASED ON SUSTAINABILITY INDICATORS

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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. Many studies have been published on how to assess sustainability using indicators that describe the different activities that impact on the environment. These can be related to the three pillars of sustainability, ecological, economic and environmental dimensions of development. Early warning indicators need to be developed that identify and monitor impacts before excessive damage on the environment occurs. As well, indicators should be able to assess the effectiveness of policies that may impact on the environment. This paper will introduce the topic of sustainable development and the formulation of sustainability indicators. Current literature emphasises the use of hierarchical sets of indicators that aim to cover environmental, sociological and economic aspects of sustainability. The paper then considers the indicators that can be assessed using remote sensing technologies and gives examples of how they may be applied in practice.

1. INTRODUCTION

In an earlier paper (Trinder et al 2002), stated that only in the past 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. Sustainable development has been proposed as a means of ensuring that human impacts are within the capacity of the Earth to cope with the changes influenced by humans. While there have been many definitions presented, *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. Alternatively, sustainable development is that which meets the needs of society today without foreclosing the needs or options of the future (Blanco et al. 2001, Mahi 2001). 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, which minimises the risk of long term degradation. 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.

Kates (2000) has reviewed the relationship between population and consumption in terms of the formula: $I=P \times C$, 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, 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.

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. For example, if tropical forest clearing is shown to be unsustainable, it cannot necessarily be terminated because it would leave those workers involved in the clearing of the forests and the use of the cleared land for farming without a livelihood.

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.'

2. TOWARDS ASUSTAINABLE COMMUNITY

Gallopín et al (2002) have compared a number of scenarios that have been used or may be used for predicting the future characteristics of a sustainable human society. They included 'market forces', 'policy reform', 'eco-communalism', through to 'muddling through'. The global community is currently dominated by market forces in which there is an absence of controls over development and therefore there are tensions between development and sustainability goals. The 'policy

reform' approach is based on the assumption of consensus and strong political will to achieve a sustainable future. In a comprehensive analysis of global political and economical developments, Radermaker (2004) compares the impact of several approaches to economic and political developments and concludes that a balanced philosophy must be based on the concept of a global 'ecosocial' market, consensus, and respect for civil rights and human equity, where human behaviour is agreed globally by social contract. It means that there needs to be a consensus on protection of resources, and respecting the need for all humans to have an adequate quality of life with access to essential resources. It is a long term view of how the global population can cooperate to secure the ecological developments, but one which he believes is essential to achieve a sustainable and equitable use of resources. Azapagic et al (2005a,b) have presented a procedure for outlining a decision making which includes all stakeholders in a development process, defining their preferences, choosing the most suitable alternative for the development, implementation of the chosen alternative, and assessment of the outcomes. The decision making process is based on the concept of Multiple Criteria Decision Analysis (MCDA), which is described in some detail.

Stevenson et al (2001) refer to the concepts developed by other authors of 'pressure', 'state', and 'response' in discussing the development of Sustainable Development Indicators (SDI) applicable for agriculture. 'Pressure' refers to human activity, such as various activities of farming; 'state' refers to 'the state of the environment and resources', eg water quality soil erosion; and 'response' refers to economic and environment agents', such as policy makers. They state that indicators are a simplification of the impact of agriculture on the environment and, that simple measures such as indicators are inadequate, without setting targets which represent levels of sustainability of agricultural activities. They argue that SDIs must provide information on which to base decisions at local or regional scale and be a guiding framework for practitioners. They have then derived a methodology for a meaningful set of indicators for agriculture that includes all stakeholders and goal setting. No actual values of indicators are given, which demonstrates that the concept of SDIs is only progressing slowly and in many cases, no assessment of the sustainability of human activity is yet possible.

While these concepts may be far removed from the practical implementation of remote sensing technologies, it can be argued that remote sensing as well as GIS have important roles to play in assisting in understanding the impacts of development and predicting unsustainable practices that are being undertaken. It must include experts in remote sensing and GIS, as well as those in ecology, biology, sociology, human resources and politics. This paper will concentrate on the concept of SDIs and their assessment using remote sensing technologies. A description will be given initially of SDIs, followed by a demonstration of how indicators can be evaluated using remote sensing. While remote sensing can be used for monitoring various aspects of land surfaces, waterways and the atmosphere, this paper will concentrate on monitoring sustainable land practices.

3. SUSTAINABLE DEVELOPMENT INDICATORS (SDIs)

Becker (1997) has defined the approaches that can be taken for assessing sustainability using 'an exact measurement of single

factors and their combination into meaningful parameters' and **indicators** 'as an expression of complex situations by a variable that compresses information into a more readily understandable form' (Harrington et al 1993). Becker (1997) has listed sustainability indicators under the headings of Economic, Environmental, Social and Composite. For example, 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.

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. SDIs are said to be designed to monitor progress and assess the effectiveness and impact of policies on natural resource development (Rao 1998). Becker (1998) reported on the proliferation of papers and recommendations on developing SDIs since the UN Rio Earth Summit in 1992. Subsequently the International Institute for Sustainable Development (IISD) has been formed, and many research and review papers have been published on SDIs. The UN, OECD, the World Bank and many other organisations have developed sets of indicators, eg Pintér et al (2005). OECD countries use 23 so-called indices based on: natural sciences, policy performance, accounting framework and synoptic indices. These are also aggregate indices that cover countries or regions.

The Government of Canada in NRTEE (2003) recommends that, in addition to the GDP and other popular economic indicators, they should report annually on a small set of indicators illustrating key aspects of natural, human and, eventually, social capital. To start with, the following indicators are recommended for use: 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. Gustavson et al (1999) studied indicators and modelling of sustainability for the Fraser River Basin in BC, Canada. They selected a large number of indicators and also suggested including a time component into the modelling. However, due to the complexity of using multiple indicators, they conclude that it is preferable to develop indicators within the areas of environmental, social, economic, and health indicators. Such indicators should be over large scale areas. They also indicate that the selection and modelling of sustainability indicators will remain an inexact science for some time.

Huetting et al (2004) view the issue of SDIs from an economic perspective, referring to Sustainable National Income (SNI) as the goal for countries. They also argue that physical aspects of the environment must be included in measures of sustainability and give the example of the cod stocks in Canada in which physical aspects were inadequately considered before the industry collapsed. Becker (1998) has provided a list of SDIs

related to social and environmental aspects. Hart (1999) has shown a new approach in SDIs which includes the interconnections between the three pillars of sustainability, ecological, economic and economic. She has stated that the indicators should be relevant, understandable, reliable and timely and has described a large number of indicators that cover many aspects of human activity, including production, energy, transport, education, health, recreation, ecosystem, land use, resource use and many more. Most of these indicators are based on such measures as: percentage of land covered by impervious materials, volumes of water used, harvest rates compared with growth rates etc. SDIs for suitability of land practices include:

- sustainable land use
- sustainable resource use
- amount of tree cover
- sustained returns
- impact on soil and/or water
- diversity of products
- conservation of native habitats.

Barrios et al (2006) have used an analytical approach, based on principal component and sparse principal component analyses of a number of core indicators of sustainable development for the Philippines, to derive relevant indicators.

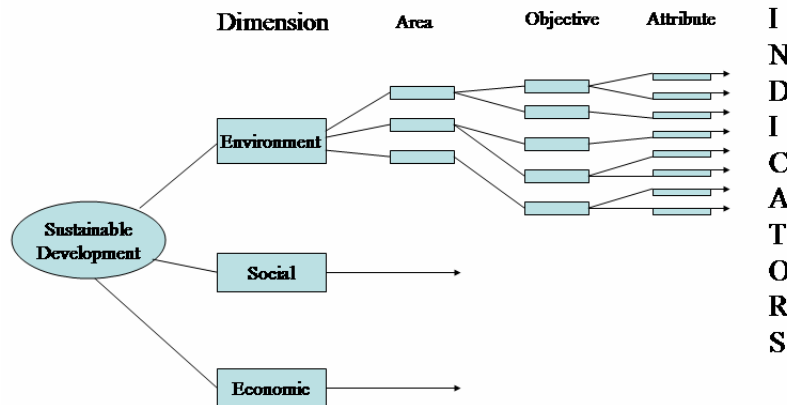


Figure 1. Hierarchical Set of Sustainability Indicators

Recent publications on SDIs have approached the development of SDIs in terms of ‘frameworks’. Olalla-Tárraga (2006) claims that a reductionist approach in which the three areas, economic, social and ecological, are separated, has failed to provide a satisfactory set of SDIs that can be practically implemented. While frameworks have not yet resulted in a useful set of SDIs, the concept is believed to lead to a better approach in the future. Olalla-Tárraga (2006) stresses the need to take an integrated approach to developing indicators for urban environments. He has presented six conceptual frameworks that have been published by various authors, namely: domain-based, issue-based, goal-based, sectoral, causal, comparative, ecosystemic, and combinations. His solution is the hierarchical concept shown in Figure 1, in which the three areas of economic, social and ecological are each subdivide into ‘area’, ‘objective’, ‘attribute’, and ‘indicators’. Links may exist between the different criteria. This is a complex approach, but one which may develop in the future. Olalla-Tárraga (2006) comments that a problem with SDIs is the limited amount of data available to compile them. Becker (2006) also provides a general discourse on frameworks for SDIs which should lead to a more holistic approach to their implementation. She states that limited tools are currently available for assessing the non-linear multi-dimensional problem of sustainable development, but frameworks can assist in understanding the issues.

In Phillis et al (2001) and Andriantiatsaholiniaina et al (2004) fuzzy logic is used to determine a combined measure of sustainability and a sensitivity to various indicators. They argue that the fragmentation of information about sustainability measures makes it difficult to assess the effects of development on the environment. Hence they attempt to use a systematic rule-based system which combines many measures of sustainability. Since these measures are never well defined, they have used fuzzy definitions of the measures, expressed

verbally in such terms as ‘good’, ‘bad’, ‘medium’ etc. A sensitivity value is determined of the factors that contribute to lack of sustainability. The research concludes that there is no unique sustainable path and, hence policies need to be chosen to determine the most sustainable strategies. Cornelissen et al (2001) have also used fuzzy set theory to link human expectations which are expressed linguistically, to sustainability indicators presented numerically.

4. APPLICATION OF REMOTE SENSING SUSTAINABLE DEVELOPMENT

Remote sensing measures many physical aspects of the environment and therefore can play a role in the measurement of SDIs, although few of the above references refer specifically to remote sensing as a contributing technology. Becker’s (1997) approach to providing criteria for developing indicators in terms of time and space has not been based on frameworks as described above, but his criteria, shown in Table 1, which have been compiled with reference to the work of a number of scientists, are very relevant to developing SDIs for physical aspects of the environment, that can be determined by remote sensing and that should be suitable for contributions to a frameworks approach to SDIs in the future. The complexity of defining sustainability indicators is revealed by the sets of criteria shown in Table 1.

1. Scientific Quality	2. Ecosystem relevance	3. Data Management	4. Sustainability Paradigm
1.1 Indicator really measures what it is supposed to detect	2.1 Changes as the system moves away from equilibrium	3.1 Cost effective	4.1 What is to be sustainable?
1.2 Indicator measures significant aspect	2.2 Distinguishes agro-systems moving away from sustainability	3.2 Data available	4.2 Participatory definition
1.3 Problem specific	2.3 Identifies key factors leading to unsustainability	3.3 Quantifiable	4.3 Adequate rating of single aspects
1.4 Distinguishes between causes and effects	2.4 Warning of irreversible processes	3.4 Representative	4.4 Resource efficient
1.5 Can be reproduced and repeated over time	2.5 Proactive in forecasting future trends	3.5 Transparent	4.5 Carry capacity
1.6 Uncorrelated, independent	2.6 Covers full cycles through time	3.6 Geographically relevant	4.6 Health protection
1.7 Unambiguous	2.7 Corresponds to aggregation level	3.7 Relevant to users	4.7 Target values
	2.8 Highlights links to other system levels	3.8 User friendly	4.8 Time horizon
	2.9 Permits trade-off detection and assessment between system components and levels	3.9 Widely accepted	4.9 Social welfare
	2.10 Can be related to other indicators	3.10 Easy to measure	4.10 Equity
		3.11 Easy to document	
		3.12 Easy to interpret	
		3.13 Comparable across borders over time	

Table 1 Criteria for the Selection of Sustainability Indicators (after Becker 1997) and adapted for their relevance to remote sensing

It is well known that in many cases remote sensing, because of the regional and multi-temporal coverage of the images, can measure many variables more economically than other field-based or manual methods. 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. While there are redundancies in Table 1, many of these criteria are relevant to the capabilities of remote sensing, particularly those in columns 1, 2 and 3.

Foody (2003) states that remote sensing can provide a wealth of environmental data over a range of spatial and temporal scales, and so may play a major role in the provision of indicators of environmental conditions, that may provide information on the sustainability of development and associated decision-making. He then discusses aspects of maps of forest and forest change, estimation of forest biomass, biodiversity, and drought, showing how remote sensing can satisfy some of the broadly based indicators referred to above, and that satellite remote sensing would be the most economical approach.

The following discussion is presented to demonstrate the positive contribution remote sensing can make to a range of sustainability indicators and adds to the contribution made by Foody (2003).

4.1 Agriculture

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.

While drought itself is evident from meteorological observations, the impact of drought on vegetation, revealed as 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.

Boyd et al (2002) studied the potentials of NOAA AVHRR middle infrared channel (3.53–3.93 μm) for identifying the effects of decreases in rainfall caused by the El Nino Southern Oscillation (ENSO) on tropical vegetation. They found that for the site in Sabah, Malaysia, that changes in canopy properties are better identifiable in MIR reflectance than by NDVI. Reflectance of MIR may therefore be an indicator of the effects of stress in vegetation caused by drought due to ENSO and other phenomena.

The European Space Agency (ESA) is using satellite data to ensure efficiency in the use of pesticides in the European region. Pesticides currently used within the EU must be registered with the national members of the European and Mediterranean Plant Protection Organization (EPPO), which requires efficiency data derived from field trials. Satellite images should be able to prove the similarity of trial sites and hence improve the procedure of mutual recognition of sites throughout Europe. While this application does not derive an indicator as such, the trial sites will enable better assessment of the impact of pesticides, and hence lead to an indicator for monitoring the impact of pesticides on the environment.

Opoku-Duah et al (2008) have attempted to understand the spatial dynamics of evapotranspiration, since it is critically important for food security and water resources management in Africa. They have shown that MODIS and AATSR can be used to derive reasonable estimates of key variables such as NDVI (a surrogate for biomass density), surface temperature and evapotranspiration over large vegetated savannah landscapes. These are key components of the energy balance equation which could prove to be used as SDIs for predicting regional water availability and ultimately food security.

4.2 Land Use Cover

Land cover change, the greatest threat to biodiversity and a major variable in the loss of nutrients from productive lands, 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. 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.

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.

Bacchus et al (2000) and Bacchus et al (2003) have investigated the detrimental effects on the health of the vegetation, in this case, pond-Cyprus, caused by the withdrawal of ground water from aquifers in Florida, USA. Since the existing space based high resolution remotely sensed data had inadequate resolution for these analyses, their investigations were based on laboratory spectrometry studies in the visible, NIR and mid infrared regions of the spectrum, of dried milled branch tips collected from natural stands of pond-Cyprus stands, both in summer and in winter prior to bud-break. They found that the NIR spectral response was more affected by stress than by site related factors. As well, they believe that the chemical changes in the vegetation that are revealed in the spectrometry studies could be used as an indicator of unsustainable withdrawal of water from the aquifers. Visual effects of stress were also evident, and they were found to be well correlated with the spectrometry studies. The paper is an important development in the use of indicators for detecting unsustainable practices, in the case, the effects of stress on the trees caused by inadequate water. While the studies are based on laboratory analyses, the spectral regions that reveal these effects may be used in future for other studies of water related stress effects on vegetation. As well, with improved future space based multispectral and hyperspectral systems becoming available, remote sensing techniques could be used for these purposes. In a similar manner, Chisolm (2006) studied moisture stress on *Eucalyptus Camaldulensis* (River Red Gum) in Australia, using high resolution spectral data at the leaf level. Her results indicate that even low levels of stress can be detected from such data before they become visible. She therefore indicated that spectral reflectance regions may be developed that would be indicators of moisture stress in vegetation and hence act as appropriate SDIs.

4.3 Transport

Zhang et al (2006) and Guindon et al (2007) have described the process for developing a set of 'Sustainable Transportation Performance Indicators' (STPI). In these papers, remotely sensed data, the basis for the land use mapping, are combined with socio-economic data derived from the national census, for the determination of such parameters as urban population density, compactness of cities, and a Transport Mode Index (TMI), that measures the impact of the land use mix and urban form on the feasibility of various modes of transportation. In this case, the data is used as a tool for the provision of the essential data. They state that while indicators are important for demonstrating the sustainability of transport systems in Canadian cities, simple measures such as density and compactness are poor indicators of energy consumption, whereas land-use mix is a better indicator. However, they argue

that more research is required to develop better indicators that incorporate median travel distance.

4.4 Land Subsidence Detection

Elevation measurements over time can demonstrate the impacts of land subsidence due to mining and ground water harvesting. As well, illegal mining activities may be detected in high accuracy elevation models over time. The impacts of ground water harvesting may also be combined with biological measurements as described above in Section 4.2. Typical methods that enable highly accurate elevation measurements, based on airborne or spaceborne interferometric SAR especially those based on permanent scatterers, can result in elevation deformation measurements better than 1cm (Cespa et al 2007) and (Ge et al 2005).

4.5 Deforestation

In Brazil, the National Institute for Space Research (INPE) has used satellite data for monitoring deforestation in the Amazon for more than 10 years. Originally Landsat images were acquired, but images from the Disaster Management Constellation (DMC) have been acquired recently for this purpose. The DMC data can be acquired over a period of about 3 months each year. INPE has developed an almost real-time monitoring system to detect illegal land clearing. High resolution images are required to determine the exact area of clearing and extracting small areas of clearing.

5. DISCUSSION AND 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 as a tool for assessing sustainable development must be related to sustainability indicators that can be measured with the technology. An attempt has been made in this paper to describe some such indicators. While remote sensing will not be the only tool for assessing indicators, it should make important contributions 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 be 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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