Use of remote sensing and GIS for sustainable land management

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ABSTRACT

Remote sensing provides the basic data to undertake inventory of land, as well as the temporal information required to monitor sustainable land management practices. In this paper, the current use of remote sensing for sustainable land management is reviewed, and the potential of future (new) satellite systems to contribute to sustainable development is explored. Other elements for successful sustainable development (ie, good policy and participatory approaches) are then compared and contrasted with information requirements.

Sustainable land management refers to the activities of humans and implies that activity will continue in perpetuity. It is a term which attempts to balance the often conflicting ideals of economic growth and maintaining environmental quality and viability. Economic activities may range from intensive agriculture to the management of natural areas.

It is argued that in order to effectively "manage" resources, three elements must be present. These are information about natural resources, clear policies on how the resource may be managed (*eg*, Acts of Government, policy papers, administrative procedures), and participation of everyone (including local people) with an interest or "stake" in the land. In this paper, we concentrate on methods to generate information about the resources, with an emphasis on how recent innovations in remote sensing fit with sustainable land management methods. In particular, we assess how resources may be inventoried by remote sensing, and techniques and data which may ascertain whether the activity is indeed sustainable. A concluding section discusses how the information (generated from remote sensing) is linked to policy and local participation.

Thus, three specific questions are addressed. First, what cover is present? This question requires that remote sensing provides information on land cover as well as terrain attributes such as slope, aspect and terrain position. The second question addresses whether the use (management) of the cover is sustainable. This question requires temporal data collection to monitor whether the environment is degrading or otherwise changing. The third question is: How can remote sensing and GIS contribute to the policy tools of generating policy, providing information and ensuring participation by all stakeholders?

SUSTAINABLE DEVELOPMENT

Sustainable development has been defined in many ways; in fact there are 67 different definitions listed in the "natural resource management" subject taught at ITC. Interestingly, none mention GIS and remote sensing as being necessary tools for sustainable development. Sustainable development is a term which attempts to balance the often conflicting ideals of economic growth and maintaining environmental quality and viability. As such, sustainability implies maintaining components of the natural environment over time (such as biologic diversity, water quality, preventing soil degradation), while simultaneously maintaining (or improving) human welfare (*eg*, provision of food, housing, sanitation, etc).

In any definition of sustainability, the key element is change; for example, Fresco and Kroonenberg [16] define sustainability as the ... dynamic equilibrium between input and output. In other words, they emphasize that dynamic equilibrium implies change and that in order for a land system to be sustainable, its potential for production should not decrease (in other words the definition allows for reversible damage). This type of definition is most applicable when considering agricultural production systems, but may also be generalized to the management of natural areas. A broader definition of sustainability, such as that proposed by Brown *et al* [6], includes the persistence of all components of the biosphere, even those with no apparent benefit to society, and relates particularly towards maintaining natural ecosystems. Other definitions emphasize increasing the welfare of people (specifically the poor at the "grassroots" level) while minimizing environmental damage [2], which has a socio-economic bias. The necessary transition to renewable resources is emphasized by Goodland and Ledec [17], who state that renewable resources should be used in a way that does not degrade them, and non-renewable resources used so that they allow an orderly societal transition to renewable energy sources.

That changes continually occur at many spatial (*eg*, global, regional, local) and temporal (*eg*, ice ages, deforestation, fire) scales is obvious to any observer. For example, change may occur in the species occupying a site, amount of nitrate in ground water or crop yield from a field. Change may also occur in human welfare indices such as health or education. To assess whether such changes are sustainable is a non-trivial problem. Possibly the greatest advantage of the debate about sustainable development is that the long-term capacity of the Earth to sustain human life through a healthy and properly functioning global ecosystem is becoming a normal political goal.

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REVIEW OF REMOTE SENSING FOR RESOURCE INVENTORY AND MONITORING

INTRODUCTION

Since the launch of ERTS-1 (Landsat 1) in 1972, digital remote sensing has been used with some success to monitor natural resources and provide input to better manage the Earth. Applications have included monitoring of deforestation, agroecologic zonation, ozone layer depletion, food early warning systems, monitoring of large atmospheric-oceanic anomalies such as El Niño, climate and weather prediction, ocean mapping and monitoring, wetland degradation, vegetation mapping, soil mapping, natural disaster and hazard assessment and mapping, and land cover maps for input to global climate models. These techniques have been developed using rather rudimentary sensing systems, such as NOAA AVHRR, Landsat MSS and TM, and Spot panchromatic. Although developments have been broadly based across many divergent disciplines, there is still much work required to develop remotely sensed images suited to natural resource management, refine techniques, improve the accuracy of output, and demonstrate and implement work in operational systems.

GLOBAL MAPPING AND MONITORING

A number of satellite systems have been dedicated to monitoring the global environment. Probably the most commonly used for natural resource management has been the NOAA AVHRR, which has a twice daily overpass and can be freely downloaded by low-cost ground receiving stations. It has a nominal pixel size of 1.1 km and records two spectral bands in the visible and near-infrared. The data from the AVHRR have been used to map global land cover (Figure 1) when degraded to a pixel size of 4 km. Land cover is an input layer to global climate models, in addition to being important for estimating the pattern of soil erosion over the Earth. AVHRR imagery has been used to estimate global biomass production (Figure 2), as well as regional estimates of biomass (Figure 3). Apart from use in global models, the imagery is also effective in awareness building of the state of the Earth’s environment, as well as policy development for government.

When used in a time series, the seasonal increase and senescence of vegetation may be related to agricultural and grassland production (see Figure 3 for Kenya). The information contained in Figure 3 forms the basis of food early warning systems in Africa; for example, in 1997 the Kenyan government imported extra grain to avoid shortages caused by drought, with the decision based partly on information derived from the data in Figure 3 [33]. FAO produces a 10-day summary of NDVI (normalized difference vegetation index), an index indicating biomass.

At a global scale, biomass production of oceans has been estimated using the coastal zone colour scanner, a NASA instrument with 825 m pixel and six channels optimized to map and monitor the oceans (Figure 4). New systems are planned, such as the SeaWifs system on the European Space Agencies ENVISAT (planned launch 1999).

Another famous satellite is the total ozone mapping system (TOMS). This satellite raised awareness of

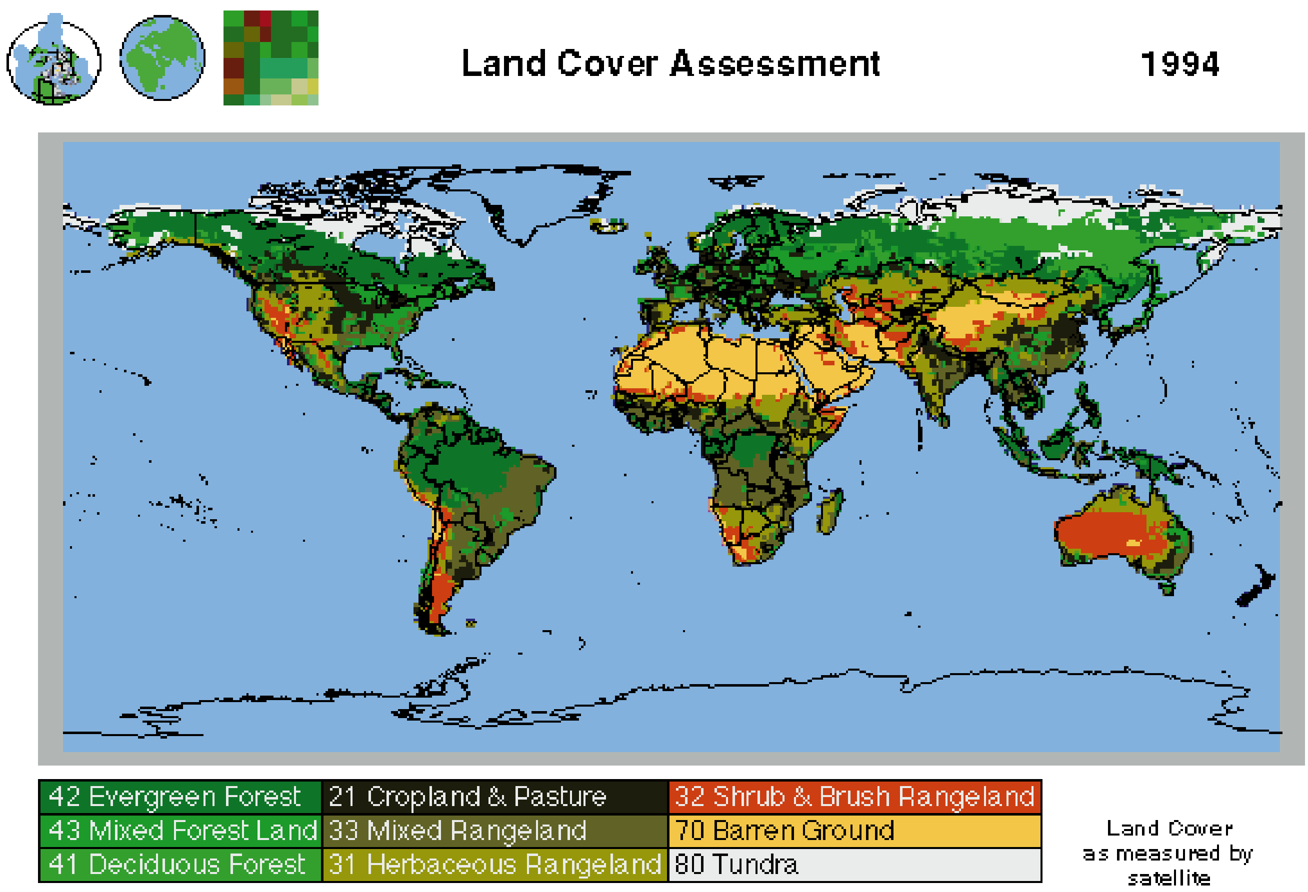


FIGURE 1 Land cover map derived from AVHRR data (source: NASA)

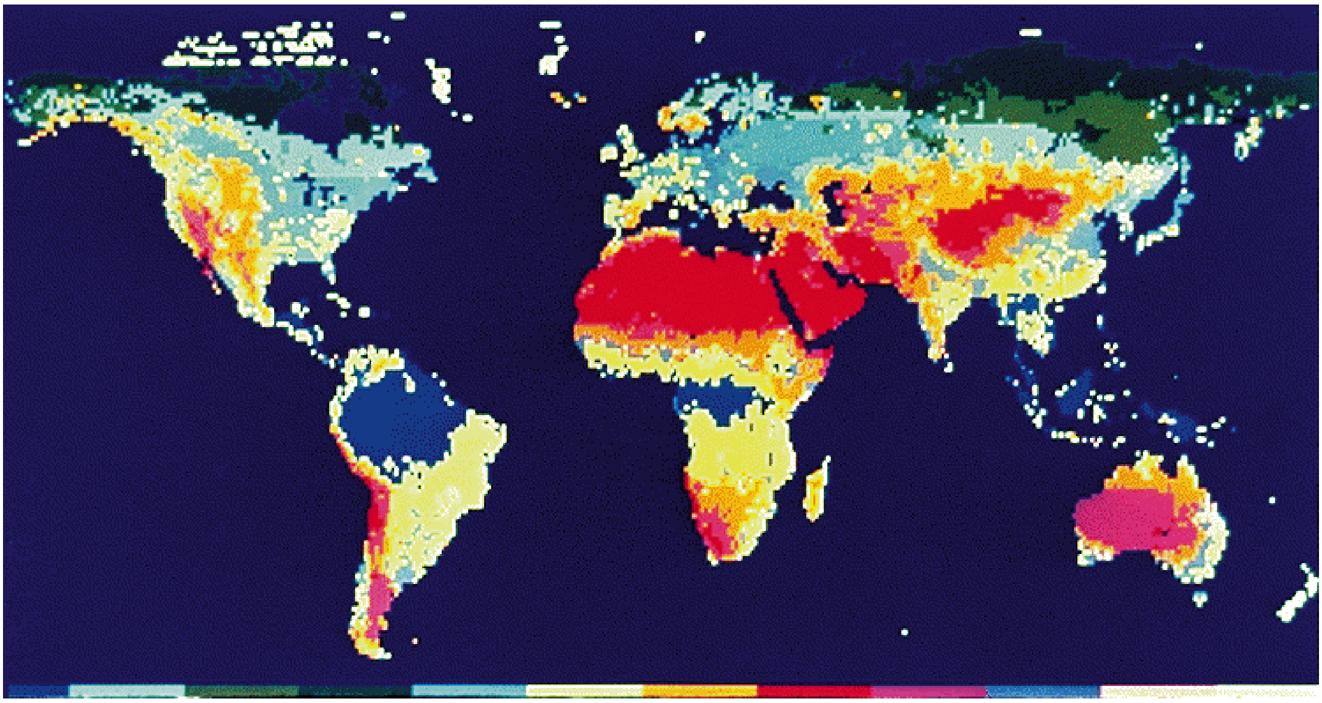


FIGURE 2 Biomass map derived from AVHRR data (source: NASA) Dark blue and green areas represent dense vegetation, pink and dark-red areas represent sparse vegetation

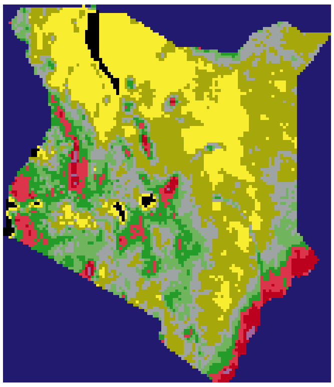


FIGURE 3A NDVI map for Kenya; average NDVI for all 10-day periods during 1981 (source: FAO). Red colour is high biomass, yellow is low biomass

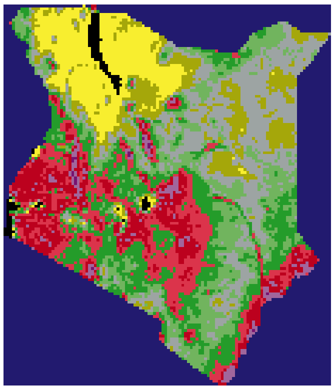


FIGURE 3B NDVI map for Kenya; average NDVI for all 10-day periods during 1990 (source: FAO). Red colour is high biomass, yellow is low biomass

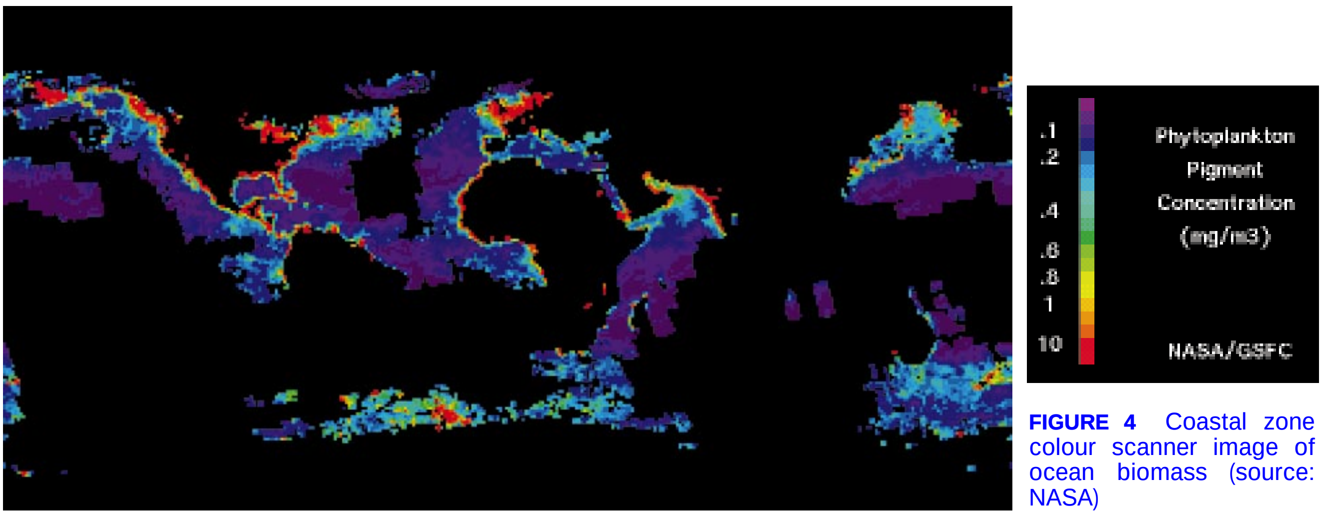


FIGURE 4 Coastal zone colour scanner image of ocean biomass (source: NASA)

ozone depletion, and assisted agreements limiting the global use of ozone-depleting chemicals.

Finally, the daily use of the global meteorologic satellite system (GMS) by weather forecasting agencies is familiar to most people (Figure 5). The GMS offers hourly updates and has two visible channels with pixel sizes of 1 km, as well as a thermal infrared channel of 5 km size.

FIGURE 5 Weather patterns derived from GMS (source: NASA)

REGIONAL MAPPING AND MONITORING

The Landsat multispectral scanner (MSS) data series commenced acquisition in 1972, and has had an unbroken data record since then. For regional-scale mapping and monitoring, the instrument has been widely used. With a 60 x 80 m pixel and four bands in the visible and near-infrared, Landsat MSS introduced multispectral remote sensing to earth resource scientists. A later sensor, called the Landsat Thematic Mapper (TM), offered higher spatial resolution (30 x 30 m) as well as more spectral bands (seven channels). Similar remote sensing sensors have been launched by other nations, such as the Indian Remote Sensing (IRS) satellite system and the French Spot.

The Landsat MSS, TM, Spot and IRS have had wide application in natural resource management, primarily in the inventory and measurement of natural resources, as well as monitoring change. An example of the utility of this type of data is shown in Figure 6, which is a Landsat MSS image from 1991 showing two arms of Macquarie Marsh in NSW, Australia. The western arm supplies water to rice growers and has been drained. A map showing the change in wetland area can be generated using imagery from 1972. Such information is essential for developing policy on the change in land cover as a result of human activity, and thereby indicating whether the activity is sustainable, from a biophysical perspective.

LOCAL MAPPING AND MONITORING

Local mapping has traditionally been undertaken using aerial photographs in combination with topographic maps (if available). The use of aerial photographs in a wide variety of applications is detailed in Colwell [8].

NEW ADVANCES IN REMOTE SENSING FOR SUSTAINABLE DEVELOPMENT

INTRODUCTION

Three recent innovations in remote sensing (*viz*, radar, hyperspectral imaging and high spatial resolution) offer promising techniques to assist sustainable development. Radar is frequently cited as a solution for mapping the structure of vegetation as well as the moisture of soils and geomorphologic patterns. Hyperspectral remotely sensed data provide information on vegetation floristics, soil type and soil chemistry. High spatial resolution images (formerly limited to "spy satellites") will offer extremely high spatial resolution images (comparable to aerial photographs) within a few hours of acquisition. These innovations are reviewed, and their potential for monitoring and mapping sustainable land management is assessed.

PART I: HYPERSPECTRAL REMOTE SENSING

Introduction

Hyperspectral imagery (also called high spectral resolution imagery) uses scanners with very many narrow bands that span a wider section of the electromagnetic spectrum from the visible to the near-infrared, compared with traditional multispectral scanners such as the Landsat MSS or TM. When the reflectance curve is plotted against the broad bands of Landsat MSS, it is obvious that the broad band scanners tend to average out important differences in reflectance over small spectral resolution (Figure 7). It is also apparent that the spectral ranges where the broad bands are placed may not

FIGURE 6 Landsat MSS image of Macquarie Marsh, NSW. Note the left-hand branch has been drained

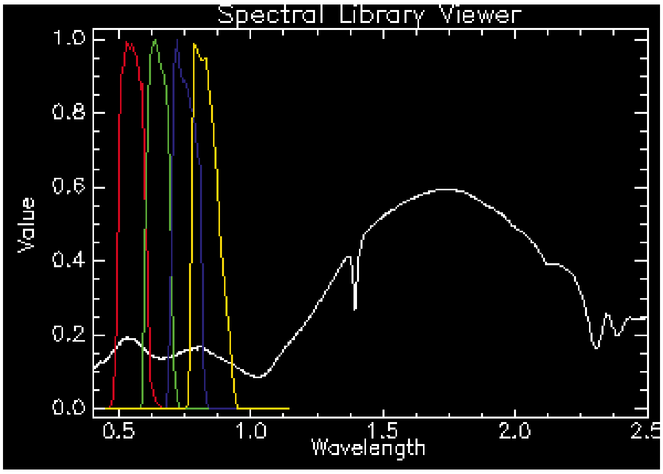


FIGURE 7 Spectral reflectance curve for mineral with Landsat MSS absorption bands superimposed in colour

coincide with the areas of maximum difference in the spectral curves for vegetation.

Hyperspectral remote sensing was developed in the 1980s through airborne systems, and in the late 1990s a number of satellite systems are planned for launch. There are at least 35 operational airborne systems.

The potential of hyperspectral remote sensing for sustainable land management is large; it represents a leap in the ability to distinguish between cover types, and hence begin to accurately monitor land degradation through, *eg*, changes in vegetation composition and structure (cover), changes in soil chemistry and structure, evapotranspiration and catchment hydrology, and forest depletion.

Main Principles

Recent successes with hyperspectral imagery have been achieved using aircraft scanners. Hyperspectral scanners are passive; in other words they receive radiation reflected from the Earths surface. At an altitude of 500 km, a spaceborne sensor receives approximately 10,000 times less radiation than an aircraft at 5 km. Therefore, much less signal (information) is received by the satellite compared with the aircraft, with a lower signal-to-noise ratio. The signal-to-noise ratio is of prime importance in hyperspectral remote sensing. With aircraft sensors, it is possible to have small pixels (say 2 to 5 m) as well as narrow wavelength bands (usually around 10 nm). With satellite systems, a choice must be made between either narrow bands coupled with large pixels (*eg*, ESA Envisat has larger pixels of 250 m and band widths of about 1 to 25 nm) or wide band widths and higher spatial resolution (*eg*, Spot XS has a pixel size of about 20 m but a few wide bands). The advantage of aircraft scanners is that spatial and spectral resolution is high, and these sensors are therefore ideally suited for detailed local surveys. However, the cost of the data is high, unless a consortium can be formed or the user is a very large organisation, and there are problems with geometric correction of the imagery due to the less stable (aircraft) platform.

In contrast, the cost of satellite data is substantially less, and will be better suited to environmental applications requiring more repetitive coverage. The challenge in the future will be to create spaceborne scanners with higher spatial and spectral resolution, while maintaining high signal-to-noise ratios.

Applications

Researchers have found relationships between vegetation properties and remotely sensed variables (Table 1). In order to summarize these diverse experiments in one table, the "cover" variable includes leaf area index, basal area and canopy cover, and the "volume and productivity" variable includes age, height, volume, diameter and density. In the body of the table, the vegetation variable is specified as well as the author of the study, date and type of remotely sensed data. For example, in Table 1 at the intersection of the "cover" column, with the "green" row, the key shows that Brockhaus and Khorram, 1992 [5] found a significant relationship between green TM band (2) with basal area of trees.

The "cover" variables of leaf area index, basal area and canopy cover have been correlated with the visible, near-infrared and middle-infrared. Red reflectance has a consistent negative correlation with leaf area index (LAI), biomass and canopy cover (Badhwar *et al* [1], Franklin *et al* [15], Tucker [48], Peterson *et al* [36], Spanner *et al* [45], Nemani *et al* [35]), and green and red reflectance with basal area (Brockhaus *et al* [4], Brockhaus and Khorram [5]). These authors also report a weak or slightly positive correlation between LAI and near-infrared reflectance. For woodlands and savannah with sparse tree cover, Franklin *et al* [14] found blue, green and red bands were strongly negatively correlated with canopy cover. Hame *et al* [20], Brockhaus *et al* [4], Brockhaus and Khorram [5] and Danson and Curran [10] note inverse correlations for tree basal area with the near- and middle-infrared, and Franklin *et al* [14] report negative correlations for canopy cover. A more complicated situation is described by Spanner *et al* [45], where forests with canopy cover greater than 89 percent exhibit positive correlation with the leaf area index, but open forests have a raised near-infrared response: between these two extremes the near-infrared response was flat. The middle-infrared wavelengths correlated with forest canopy closure [7] and leaf area index [45]. Peterson *et al* [36] reported a strong relationship between leaf area index and a near-infrared/red ratio, but Spanner *et al* [45] found a confused relationship with this ratio. The normalized difference vegetation index (NDVI) ratio was weakly correlated with canopy cover [14]. However, Nemani *et al* [35] concluded that NDVI cannot be used to estimate LAI for open canopy conditions.

With respect to the "volume and productivity" variable in Table 1, Turner *et al* [50] and De Wulf *et al* [12], showed that Spot bands in the visible were not significantly correlated with any forest plantation parameters, but De Wulf *et al* [12] noted that the Spot panchromatic band, which spans the visible, correlated with stand density and average canopy height. In contrast, Danson and Curran [10] reported that the red radiance correlated with age, density, DBH and height, and Fiorella and Ripple [13] found a correlation between the visible bands and mature and old-growth forests. Skidmore and Turner [42] found that as age varied for coniferous plantations, different Landsat MSS responses were recorded.

When considering the "volume and productivity" variables at infrared wavelengths, Turner *et al* [50], Leprieur *et al* [28], Hame *et al* [20] and Danson and Curran [10] reported that the near-infrared band had a significant negative relationship with age; however, Hame *et al* [20] reported that the near-infrared band was correlated with tree volume (which conflicts with the results of Turner *et al* [50] and Leprieur *et al* [28]) as well as mean tree diameter. Again in contrast with the above results, Danson and Curran [10] discovered the near-infrared correlated with density, DBH and height. The middle-infrared wavelengths correlated with stem density [25], while Leprieur *et al* [28] concluded that middle-infrared reflectance decreases with increasing stand age. Thermal infrared was correlated with forest structural characteristics [23]. More recent work by Fiorella and Ripple [13] found that ratios of near-infrared/red and near-infrared/middle-infrared correlated with structural forms.

Cook *et al* [9] discovered that vegetation productivity is more strongly related to band ratios than individual bands. Ratios of middle-infrared to near-infrared, as well as ratios of middle-infrared and visible (blue), were important. In mountainous sites, Cook *et al* [9] found that Landsat TM band 6 (thermal infrared), in varying ratios with visible bands, correlated significantly with productivity.

Horler and Ahern [24] found the red, near-infrared and middle-infrared useful for discriminating Canadian forests. Nelson *et al* [34] analyzed (simulated) TM data, and concluded most information about vegetation was contained in the blue, near-infrared and middle-infrared. Thermal infrared was used by Holbo and Luvall [23] to map broad forest type classes.

Vegetation dieback and damage are best mapped by band ratios. Rock *et al* [39] and Vogelmann and Rock [52] correlated thermal/middle-infrared and thermal/near-infrared ratios with dieback in high altitude spruce-fir forests, and Defeo *et al* [1] found the middle-infrared/near-infrared ratio significant. Vogelmann [51] concluded that NDVI was more suitable for monitoring broadleaf forest damage, while a ratio of middle-infrared to near-infrared was best for both coniferous and broadleaf forests. Leckie *et al* [27] concluded that ratios and normalized differences of the spectral bands best discriminated spruce budworm damage.

The impact of terrain on vegetation reflectance values has been widely reported, as forested areas often occur over rugged areas. For example, Hoffer [21] improved the accuracy of remote sensing classifications by including elevation, while Strahler *et al* [46, 47] also improved mapping by incorporating topographic data (*ie*, slope, aspect, elevation). Richards *et al* [38] and Skidmore [41] used topographic information with Landsat TM data to improve forest type mapping.

Areas which are shadowed as a result of topography will have lower mean and variance brightness values compared with areas which are sunlit [22, 25]. However, increasing the brightness of shadowed areas (that have a low variance) will not increase the amount of information content *per se*. Shadow in remotely sensed images is in part determined by the steepness of the topography [19]. Leprieur *et al* [28] also investigated the relationship between slope gradient and reflectance, but found the relationship was confused by variations in the vegetation cover. Aspect is an important terrain variable which influences remotely sensed reflectance; for example, Proy *et al* [37] found that well illuminated pixels are not influenced by scattered sky irradiance, but shadowed pixels require adjustment for this effect. Another problem highlighted by Karaska *et al* [26] was the percentage of tree and shrub cover, which masked the effect of topographic variables on spectral responses. There has been some debate whether Lambertian (*ie*, light is scattered equally in all directions from a surface) or non-Lambertian models are more suited for modelling topographic shadowing [30, 25], although Smith *et al* [44] and Holben and Justice [22] showed that ponderosa pine and sand will exhibit both Lambertian and non-Lambertian scattering at different sun incident angles. Thus, as Justice *et al* [25] stated back in 1981, reducing topographic effects in remotely sensed data by using digital terrain models is difficult; and even today this topic remains inconclusive.

Two recent experiments have been undertaken by the authors in eucalypt forests of NSW, Australia, and the rangeland of the Masai Mara Nature Reserve, Kenya. In both experiments, the principle aim was to evaluate whether species may be distinguished based on the spectral response. In addition, work is underway to try and scale up the spectral response of the individual species to the response obtained for a pixel.

The grassland studies at Masai Mara Nature Reserve show that there are significant differences between eight grass species. In these experiments, the spectral position of maximum difference was at the visible-red (around 600 to 700 nm) and the near-infrared—middle-infrared (approximately 1200 to 1600 nm) (Figure 8). The statistical difference between the different grass species (as tested using the student's t-test) is indicated on Figure 9; the vertical shading indicates the number of species which had a statistically different reflectance for the various wavelengths. Note that with eight species, a total of 28 possible combinations of species may be available. Another interesting result is that the area of the spectrum which best discriminates senescence of vegetation (based on a two-week period when *Themida triandra* was senescing or "haying off") was also at the same wavelengths (Figure 9). Clearly this has implications for the choice of suitable wavelengths for discriminating vegetation in scanners, and requires further study.

The geologists have made advanced use of hyperspectral data. An example is shown in Figure 10, where the spectral response curve for kaolinite is measured at 2 mm by a spectrometer (PIMA-II) and at 22 km by the

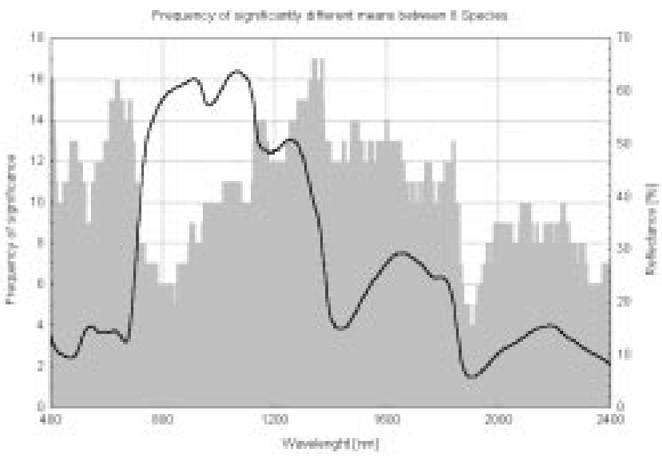


FIGURE 8 Reflectance curve for vegetation with grey shading representing the number of significant differences between the eight grass species in Masai Mara Nature Reserve

AVIRIS scanner. The characteristic absorption pits, as well as similarity between the two curves should be noted. The popular "linear unmixing" method of classifying the percentage of cover components within a pixel has been developed for hyperspectral data [3].

Another interesting application is the use of the middle-infrared to measure atmospheric water vapour (Figure 11). Such studies may be extended to mapping evapotranspiration. Evapotranspiration or water vapour maps may be used as input (independent) variables for crop growth models, drought prediction, land suitability and capability assessment, as well as catchment and water balance applications.

Hyperspectral data are frequently displayed as "image cubes", where an image (usually a colour composite) represents the surface, and the bands (*eg*, 224 for AVIRIS) are detailed on the sides of the cube, going from short wavelengths at the top of the cube to longer wavelengths at the bottom of the cube. As shown in Figure 12, the image cube may allow anomalies to be visualized; in this case, a saltwater pool with red shrimp swarms has an obviously different spectral response compared with virtually total absorption of water (see arrow on Figure 12).

Finally, hyperspectral data may be used for natural disaster monitoring, especially with aircraft-borne systems which permit rapid response. For major catastrophes, high spatial resolution panchromatic images (or serial photographs) may suffice (see below for the description of new high resolution satellite images). But if a detailed classification, such as the deposition of silt and sand after a flood, or the pattern of burnt vegetation after a fire, must be mapped, then hyperspectral data should provide a higher classification accuracy.

PART II: RADAR REMOTE SENSING

Introduction

Since the 1970s, imaging radar has been used to map natural resources, first from aircraft and since 1991 from satellite platforms. Few sensors in the microwave section of the spectrum work with the reflected/emitted radiation of the Earth itself, like sensors in the optical and infrared section do. Most radar sensors used for mapping and monitoring natural resources are active

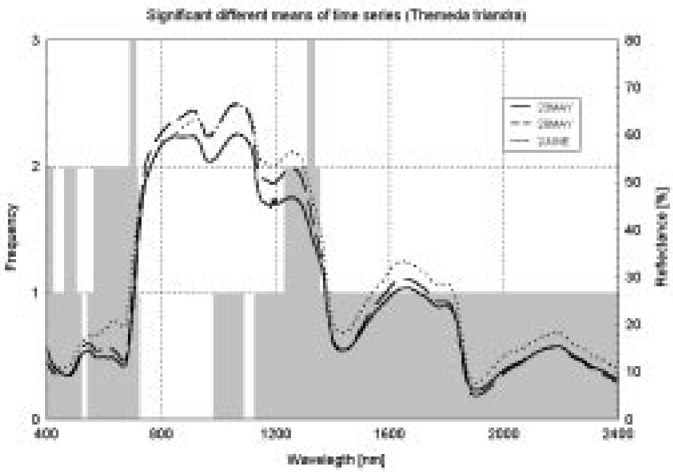


FIGURE 9 Time series for senescing of grass over three weeks. Grey shading represents wavelengths at which there are significant differences between the three dates

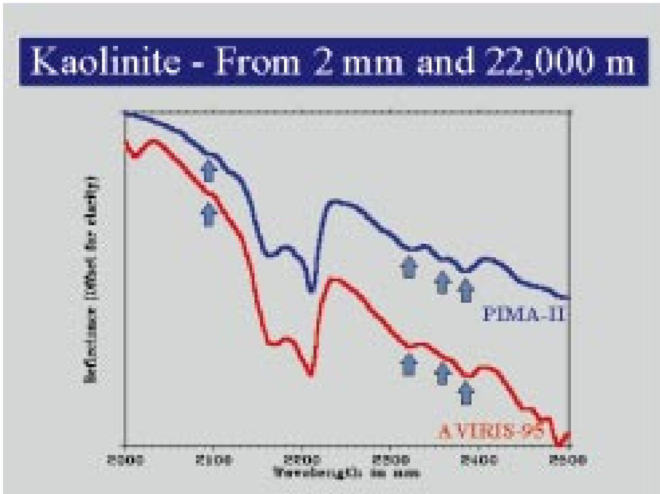


FIGURE 10 Reflectance of kaolinite from 2 mm (PIMA-II) and 22 km (AVIRIS) (source: NASA)

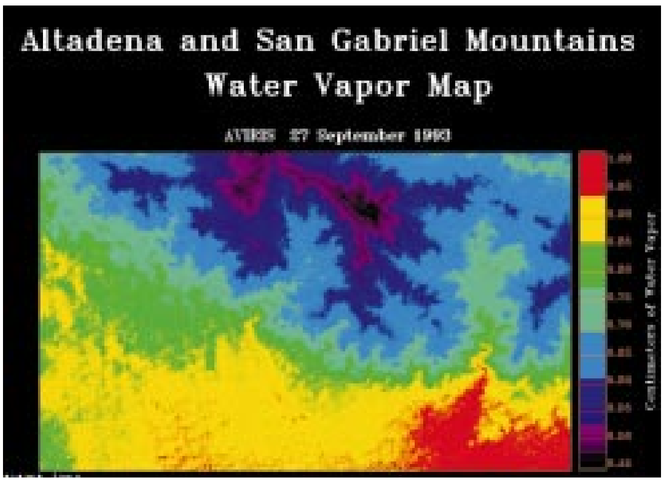


FIGURE 11 Water vapour map prepared using AVIRIS (source: NASA)

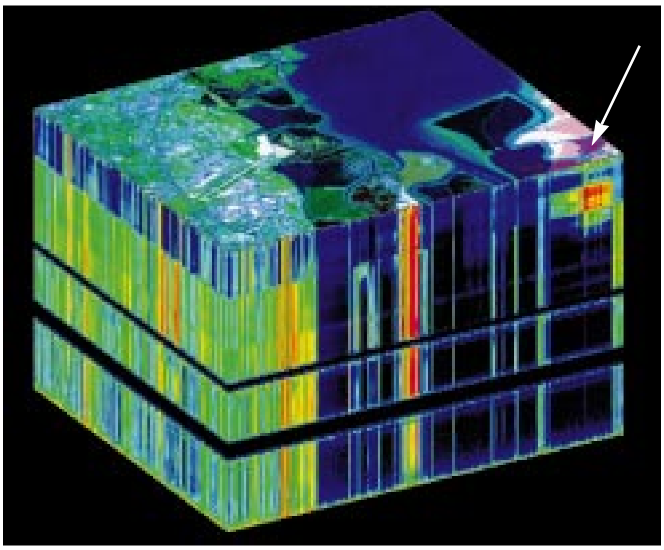


FIGURE 12 Image cube prepared using AVIRIS (source: NASA)

sensors, receiving the reflection of the radiation they emit themselves. This has the advantage that the sensor can be used any time during night or day. As the wavelengths used are in the order of a few millimeters to nearly 70 centimeters, the radiation is not reflected or absorbed by clouds or haze. This is especially important in a large number of humid areas, where optical or infrared sensors are of limited use for mapping and monitoring natural resources because of clouds and haze.

Main Principles

The microwave radiation emitted by the sensor reaches the surface and is scattered. Part of the scattered signal is received by the sensor; this is called the backscatter. The intensity of the backscatter depends on characteristics of the sensor and of the scattering surface. To start with the latter, generally backscatter increases with the amount of moisture in the soil and the vegetation and with the roughness of the surface (both canopy as well as soil surface). The longer the wavelength used, the deeper the waves will penetrate the vegetation or the soil surface. The backscatter in X- and C-bands gives information on the upper few centimeters of a bare soil, or the upper part of the canopy of a closed forest. The L-band will penetrate a few decimeters into a bare soil, depending on the moisture content, and gives information on the larger branches of the trees in a closed forest. The P-band penetrates deeper into the soil, and gives information on the trunks in the forest, and on the understorey. This illustrates that a combination of several wavelengths will make it possible to make moisture profiles in soils as well as see differences in the distribution of biomass in forests. In vegetation with less biomass and/or a more open canopy, backscatter will be influenced by both soil as well as vegetation characteristics.

Polarimetry refers to the study of how the polarized (horizontal or vertical) radar electromagnetic radiation is scattered by the surface. Traditional radar sensors could transmit microwaves in a vertical or horizontal mode, and then receive the reflected vertical or horizontal mode. In other words, there were four possibilities *viz*, V-V (*ie*, receive vertical and transmit vertical), H-H (*ie*, receive horizontal and transmit horizontal), H-V (*ie*, receive horizontal and transmit vertical), and finally V-H (*ie*, receive vertical and transmit horizontal). More recently, multipolarized images may be generated (based on the Stokes matrix) which allow all combinations of polarization between vertical and horizontal to be simulated. The polarimetry images provide further insights to the structure and floristics of vegetation, soil properties and parent material.

By using a time delay (difference) in recording a radar image as a satellite or aircraft proceeds along a flight line, a digital elevation model may be generated by interferometry. An interesting application has been the monitoring of the recent Iceland volcanic eruption which occurred under a glacier (Figure 13). The change in elevation of the glacier (due to meltwater under the ice having a smaller volume than the ice) was monitored by interferometry with high accuracy, and the volume of meltwater was accurately predicted (see http://isis.dlr.de/info/news/volcano for the interferometry of the volcano on Iceland erupting). In this case, the radar was invaluable as the area is cloudy, and the change in the glacier could not be monitored by conventional remote sensing methods. Other application areas which may benefit from these techniques include areas of mine subsidence, as well as mud slips.

Finally, benefits of the satellite radar systems are stable platforms offering well-calibrated data. There are no problems with haze, smoke or cloud, and consequently atmospheric corrections are not required.

PART III: HIGH SPATIAL RESOLUTION IMAGERY

Introduction

By 1998, high-resolution "spy" satellite images should be available at low cost, with delivery within a few hours. Two competing American companies, Space Imaging EOSAT and Earthwatch, plan to launch satellites with pixel sizes of 1 m and 3 m, respectively. A second satellite will be launched by Earthwatch in 1999 and will have a resolution of 85 cm.

Main Principles

These commercial systems are being built by the same companies which developed spy satellites for the American military. The satellites have a telescope which can be rotated up to 30 degrees off nadir, to point at targets nominated by customers. The sensors are

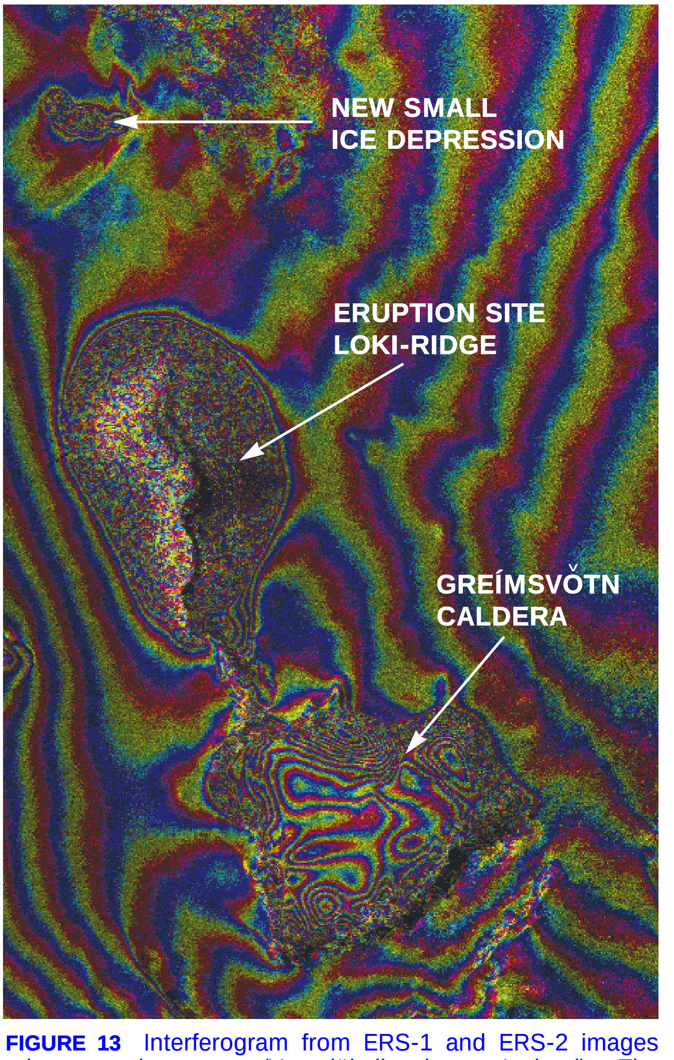


FIGURE 13 Interferogram from ERS-1 and ERS-2 images taken two days apart (Vatnajökull volcano, Iceland). The pear-shaped depression in the middle of the image is the volcanically active area (source: DLR, Germany)

arrays of charge coupled devices (similar to the Spot sensor system). The closest current competitors are the Spot panchromatic system, with a resolution of 10 m, as well as former Russian military photographs with a 3 m resolution (Figure 14). The Russian photographs have a limited coverage, and delivery has been slow and difficult, although a US distributor is now working effectively.

There is nothing particularly new about high spatial resolution technology; it has been known informally for many years that military satellites are able to resolve objects as small as 10 cm. The difference is that this high resolution imagery was only available through aerial photographs. Aerial photographs are expensive to obtain (or buy), and natural resource managers often have restricted access in developing countries due to "security concerns".

The new satellites will offer lower resolution than the military systems, but will deliver imagery just as quickly. It is the ability to rapidly acquire images which should be of most use for natural resource management and sustainable land use.

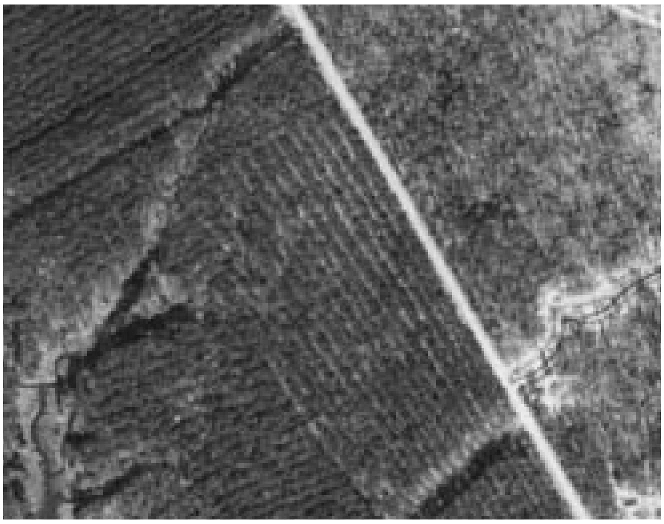


FIGURE 14 High spatial resolution imagery (source: Russian Space Photograph Archive)

Applications and Potential for Sustainable Land Use

The low cost of the imagery is an obvious advantage for natural resource managers, particularly in developing countries. Urban planners will also find the imagery of great interest (Figure 15). Another potentially useful application is the use of this imagery for map making—updating maps is slow and expensive, and a number of agencies have been using satellite imagery or orthophotographs as a base over which traditional cartographic line work (*eg*, roads, rivers, cadastre, etc) are placed (Figure 16).

Perhaps the greatest advantage of rapid delivery of images is for checking and control of human activities and impacts. This will allow users to monitor new developments, as well as design methods to assess whether environments are degrading as a result of resource utilization.

Ironically, military applications may benefit; an application which is often considered counter-intuitive for sustainable land management. The images will allow strategic targets to be identified and mapped, as well as

FIGURE 15 Dallas (USA) with simulated 1 m resolution data (source: Russian Space Photograph Archive)

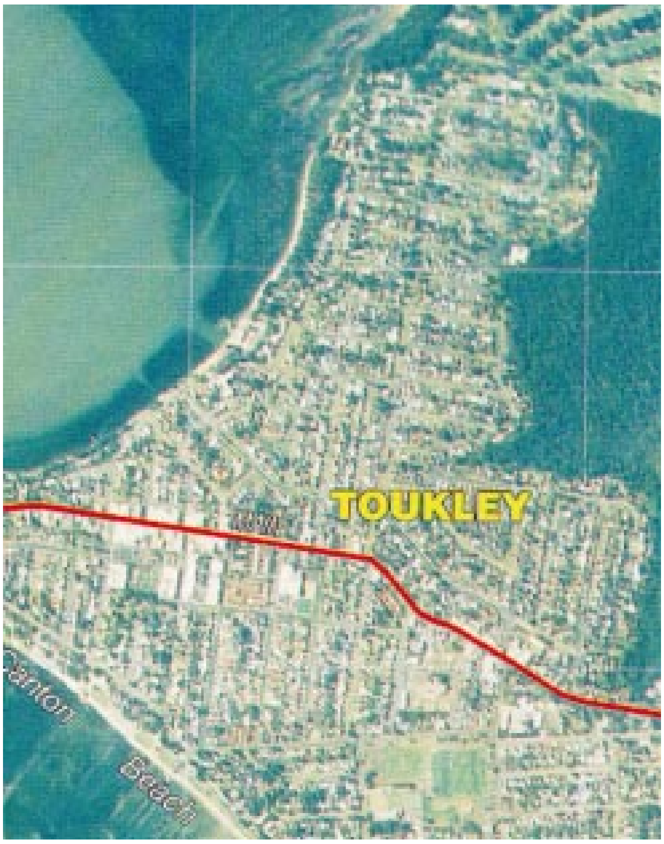


FIGURE 16 Topographic map prepared from orthophoto and digital line work (source: Land Information Centre, Bathurst, Australia)

priming missile guidance systems with the necessary coordinate systems. On the other hand, the publicly available data will make the build-up of arms (such as building missile bunkers) much more transparent to the rest of the world.

PROMISING ALGORITHMS FOR SUSTAINABLE DEVELOPMENT

Visualization is an important tool for assessing the impact of a development. Three examples are shown. The first (Figure 17) details a land cover map classified from remotely sensed data draped over an elevation "grid". Such applications are useful for land suitability studies, change detection and obtaining knowledge about where in the landscape particular land cover, or land cover changes, are occurring. The second example (Figure 18) was produced by draping an aerial photograph of water and forest over a DEM wire frame. A forester then prescribed the areas proposed to be clearcut, and these areas are "visualized" by replacing the forest aerial photograph, with a "cookie cut-out" of a cleacut area. A third "visualization" example, designed to reduce the production cost of topographic maps, is to superimpose cartographic line work (*eg*, transport, cadastre, hydrographic features) onto a orthophotograph or high resolution satellite image (Figure 16).

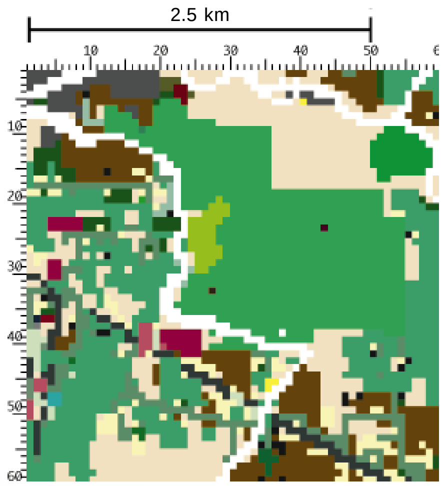
A second technique holding promise is the expert system [43]. In this technique, knowledge about a resource is formalized as a set of rules, which may be used to classify digital spatial data. Operational accuracies have been achieved. These techniques may be particularly relevant when used in combination with information obtained from participatory rural appraisal (PRA) and rapid rural appraisal (RRA) methods (see below for details).

POLICY TOOLS AND INFORMATION NEEDS FOR SUSTAINABLE DEVELOPMENT

In recent years, new approaches to natural resources management have emerged, based on the participation of local populations, such as joint forest management, social forestry and eco-development projects. Approaches ignoring local knowledge and stakeholder interests have sometimes had poor conservation success, while simultaneously failing to meet the needs of the local population. Survey and planning techniques with a local focus have been termed PRA (participatory rural appraisal), while RRA (rapid rural appraisal) are applicable for larger areas at higher administrative levels and map scales [31, 32]. But the inclusion of socio-economic approaches and data must be consistent with conventional scientific methods in order to avoid bias, maintain credibility, and check the veracity of the output.

Indeed, both socio-economic and biophysical approaches may be combined, in order to provide data and information for decision makers and the planning process. Successful examples of biophysical studies at the local scale (*eg*, [43]) and regional scale [49] have the potential to be used with socio-economic data collected at similar scales (*eg*, PRA for local (*eg*, [40]) and RRA at a regional level). Integration is facilitated though site-specific data collection, where biophysical and land use data are collected for the same plot and are directly cross-checked and integrated.

For most natural resource applications (*eg*, forestry, agriculture, nature conservation), a people-centered approach must be joined with a biophysically based approach, if the use and conservation of natural resources are to be balanced. Both approaches may be supported by remote sensing and GIS. Some attempts at integrating participatory methods with remote sensing and GIS have been made (*eg*, [40, 18]). Maps of biophysical resources for policy and district management plans are usually derived by aerial photographs (and more recently by digital image processing and GIS). Further research into the issue of a multi-scale interac-



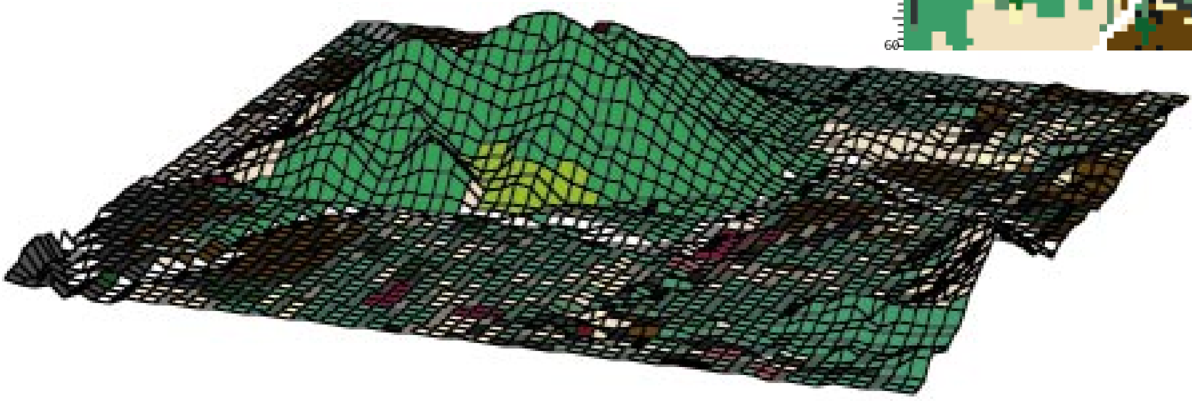


FIGURE 17 Drape of classified image over a digital elevation model

TABLE 1 Literature references of relationships between vegetation properties and remotely sensed variables

R.S. Band	*Forest variable* *Cover*	*Volume and productivity*	*Type*	*Damage*
Blue	• Franklin *et al* 1991, [14]—COVER—TM	• Fiorella & Ripple, 1993 [13]—AGE—TM	• Lillesand *et al*, 1985 [29]—TM • Nelson *et al*, 1984 [34]—TM	• Leckie *et al*, 1992 [27]—TM
Green	• Brockhaus & Khorram, 1992 [5]—BA—TM • Franklin *et al*, 1991 [14]—COVER—TM	• Fiorella & Ripple, 1993 [13]—AGE—TM • Brockhaus & Khorram, 1992 [5]—AGE—TM	• Lillesand *et al*, 1985 [29]—TM	
Red	• Badhwar *et al*, 1984 [1]—LAI—TM • Franklin *et al*, 1986 [15]—LAI—TM • Franklin *et al*, 1991 [14]—COVER—TM • Tucker, 1979 [48]—LAI—MSS • Peterson *et al*, 1987 [36]—LAI—TM • Spanner *et al*, 1990 [45]—LAI—TM • Brockhaus & Khorram, 1992 [5]—BA—TM • Nemani *et al*, 1993 [35]—LAI—TM	• Skidmore & Turner, 1988 [42]—AGE—TM • Brockhaus & Khorram, 1992 [5]—AGE—TM • Danson & Curran, 1993 [10]—AGE • —AV HT • —DBH • —VOL	• Horler & Ahern, 1986 [24]—TM	
Pan visible		• De Wulf *et al*, 1990 [12]—AV HT—S • De Wulf *et al*, 1990 [12]—VOL—S	• Horler & Ahern, 1986 [24]—TM • Nelson *et al*, 1984 [34]—TM	
Near-IR	• Hame *et al*, 1988 [20]—BA—S • Brockhaus & Khorram, 1992 [5]—BA—TM • Brockhaus *et al*, 1988 [4]—BA—TM • Danson & Curran, 1993 [10]—BA—TM • Badhwar *et al*, 1984 [1]—LAI—TM • Franklin *et al*, 1986 [15]—LAI—TM • Franklin *et al*, 1991 [14]—COVER—TM • Tucker, 1979 [48]—LAI—MSS • Peterson *et al*, 1987 [36]—LAI—TM • Spanner *et al*, 1990 [45]—LAI—TM	• Fiorella & Ripple, 1993 [13]—AGE—TM • Brockhaus & Khorram, 1992 [5]—AGE—TM • Turner *et al*, 1988 [50]—AGE—S • —AV HT—S • Hame *et al*, 1988 [20]—AGE—S • —VOL—S • —DBH—S • Leprieur *et al*, 1988 [28]—TM—AGE—TM • Danson & Curran, 1993 [10]—AGE—TM • —AV HT • —DBH • —VOL	• Horler & Ahern, 1986 [24]—TM • Nelson *et al*, 1984 [34]—TM	
Middle-IR	• Brockhaus & Khorram, 1992 [5]—BA—TM • Butera, 1986 [7]—COVER—TM • Franklin *et al*, 1991 [14]—COVER—TM	• Brockhaus & Khorram, 1992 [5]—AGE—TM • Leprieur *et al*, 1988 [28]—AGE—TM • Horler & Ahern, 1986 [24]—VOL—TM	• Horler & Ahern, 1986 [24]—TM • Nelson *et al*, 1984 [34]—TM • Tucker, 1979 [48]—MSS	
Ratio	• Nemani *et al*, 1993 [35]—LAI—modified NDVI—TM	• Cook *et al*, 1989 [9]—PROD—TM—MIR/NIR • —PROD—TM—MIR/blue • —PROD—TM—TIR/vis • Fiorella & Ripple, 1993 [13]—AGE—TM NIR/red • —AGE—TM—MIR/NIR		• Leckie *et al*, 1992 [27]—NIR/red—TM • —norm-diff—TM • Defeo *et al*, 1987 [11]—MIR/NIR—TM • Rock *et al*, 1986 [39]—TIR/MIR—TM • Vogelmann & Rock, 1986 [52]—TIR/MIR—TM • Vogelmann & Rock, 1986 [52]—TIR/NIR—TM • Vogelmann, 1990 [51]—NDVI, MIR/NIR—TM

Terrain		• Hall-Könyves, 1987 [19]—gradient—TM • Karaska *et al*, 1986 [26]—gradient—TM • Strahler *et al*, 1980 [46]—gradient—TM • Hoffer, 1975 [21]—elevation—Skylab • Strahler *et al*, 1980 [46]—elevation—TM • —aspect • —gradient • Skidmore, 1989 [41]—TM—aspect—TM • Richards *et al*, 1982 [38]—aspect—TM

Key
- Forest variables: BA = basal area; LAI = leaf area index; COVER = crown cover; AV HT = average stand height; VOL = stand volume; DBH = diameter at breast height; PROD = forest productivity
- Terrain variables: gradient = slope gradient; elevation = altitude or elevation
- Remote sensing bands: blue = visible blue; green = visible green; red = visible red; NIR = near-infrared; MIR = middle-infrared
- Remote sensing ratios: NIR/red = near-infrared to red ratio; MIR/NIR = middle-infrared to near-infrared ratio; TIR/MIR = thermal-infrared to middle-infrared ratio; TIR/NIR = thermal-infrared to near-infrared ratio; norm-diff = normalized difference
- Remotely sensed data source: TM = Landsat Thematic Mapper; S = Spot; MSS = Landsat MSS; Skylab = NASA Skylab data

FIGURE 18 Visualization of proposed forest operations. Aerial photographs draped on a DEM "wire frame"

tion and communication between different planning levels represents a major challenge.

However, it should be emphasized that there are three essential components for any sustainable development. These are:

(1) *Information:* Information on which to base planning and decision making, and to monitor whether the activity is indeed sustainable, through change detection. In recent times, less emphasis has been placed on good data and information supply by donor organizations, government and industry. Exceptions are the wildlife and livestock records, as well as agricultural production figures, which have been collected for 20 years by the Department of Remote Sensing and Resource Assessment, Nairobi. From this time series data, conclusions may be drawn about the decline of wildlife, famine early warning systems and increasing livestock populations.

(2) *Policy:* Clear and unambiguous policy is required at global, national, regional and local levels, to guide the planning and utilization of resources.

(3) *Participation:* Unless stakeholders (at all levels) are involved in considering the consequences of their actions, then a development will not be sustainable.

Equally important is to have a well educated society which can consider and debate the consequences of the development.

CONCLUSIONS

In this paper, a small selection of successful remote sensing applications in the area of sustainable development have been reviewed. Three recent types of remotely sensed imagery (high spatial resolution, hyperspectral, and radar) are discussed, and the potential outlined. Finally some methods for using and integrating these data with appropriate algorithms and planning environments are discussed. Any sustainable development should balance information supply, good policy and participation.

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RESUME

La technique du remote sensing nous fournit les données fondamentales pour dresser un inventaire du territoire en même temps qu'elle met à notre disposition les informations temporelles dont il est besoin pour surveiller les procédés de l'aménagement soutenable du territoire. Le travail de recherche que voici s'applique à examiner la technique du remote sensing dont on se sert en ce moment dans l'aménagement du territoire. Il vise aussi à explorer le potentiel inhérent aux systèmes satellites à venir de contribuer à un développement soutenable. Enfin, ce travail met en comparaison d'autres éléments indispensables à un développement soutenable promis au succès (c-à-d, une bonne politique et des procédés participatoires), et fait ressortir le contraste entre ceux-ci et les exigences d'information.

RESUMEN

La teledetección provee los datos básicos para emprender el inventario de las tierras, así como la información temporal requerida para monitorear prácticas de manejo sostenible de las tierras. En este artículo, se revisa la utilización corriente de la teledetección para el manejo sostenible de las tierras, y se explora el potencial de sistemas satelitarios futuros (nuevos) para contribuir al desarrollo sostenible. Luego se comparan otros elementos que promueven el desarrollo sostenible exitoso (por ejemplo, buenas políticas y enfoques participatorios) y se contrastan los mismos con los requerimientos de información.