Applications of GIS and Remote Sensing Technology for Agro-Environmental Issues in Less Developed Regions

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Abstract

Alternative viewpoints about the utility of land range in emphasis from production to conservation. In other words, land can be considered as a source of food, living space and materials that support human life - a viewpoint emphasizing the use of land for production. But an alternative view is that land supports global ecosystems on which humans are dependent for future survival - a viewpoint based on conservation. Balancing human activity and agricultural production in order to feed people and provide the necessities of life, can conflict with the objectives of nature conservation. My aim in this presentation is to critically review the issue of production versus conservation, and examine the role of remote sensing and GIS in finding solutions.

It is argued that sustainable land development should be based on:

* effective and clear national and regional policy and leadership
* participation by, and benefits to, local people (managers, landowners, stakeholders)
* an active non-government organization network to maintain accountability.

All these elements require the provision of timely, accurate and detailed information about land resources. This spatial information can be provided through GIS and remote sensing. By integrating disciplines and technologies, better information and maps will lead to improved planning, decision-making and hopefully generate harmony between production and conservation across a landscape. A number of successful applications of GIS and remote sensing for solving and managing land-related problems in less developed countries are described. In addition, new remote sensing systems that offer exciting possibilities for mapping and monitoring of land resources, will be introduced.

As human demand increases to access and use limited natural resources, how may future GIS and remote sensing assist in finding solutions? GIS is being widely and rapidly adopted. But constraints and problems remain in combining GIS and remote sensing for operational use. Part of the problem is due to the fact that satellite remote sensing has played a relatively minor role in the commercial success of GIS. There are other reasons for the poor uptake of remote sensing, of which five appear to dominate, and these will be discussed. A map of the presentation is outlined in Fig. 1.

Agro-environmental problems

The world's population continues to increase at a rapid rate and is predicted to reach around 10 billion people in approximately 50 years (United Nations Population Division, 1993). The current population of 6 billion people is unevenly distributed (Livernash, 1994), densities being highest in East Asia, Northwest and Central Europe, and the Indian subcontinent. Population increases will occur predominantly in developing countries; population is predicted to triple in Africa, rise by 2.5 times in Latin America and one third in Asia, with a slight increase in population (due to migration) in the developed world (United Nations Population Division, 1993). The

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increase in population is attributed to an increasing life expectancy (due to better health care, sanitation and clean water supplies), and a larger base population[1].

An almost doubling of population will place increased demands on natural resources as more food, fuel, clothing, housing, water, energy, and other necessities of life will be required. The capacity of the land to meet present demands is being exceeded at a local and regional level: there are many examples of loss of habitat, extinction of species, famine, severe soil erosion and degradation, water shortages, fragmented and degraded forests, and pollution of soil, water and air.

Globally, land resources are being used more intensively, and the use is changing. Table 1 derived from Deevey (1971) details the dramatic changes in land use over approximately the last 300 years. A process of frontier expansion continues in many tropical and mountain regions such as the Amazon, West Africa, South and East Asia, and the Himalayas, following a pattern of economic development through agricultural expansion achieved during earlier periods in regions such as West Asia, Europe, North America and Australia. There is also concern that the global environment is being affected by humans - examples include global warming, ozone layer depletion, loss of biodiversity and habitat, and so on.

The area of land on earth is approximately 13,040 million ha; oceans are more extensive at approximately 31,500 million ha. In summary, slightly less than one-third of the land is forest, slightly more than one-third farm land, and the rest exists in a natural or semi-natural state, occupying ecological zones unsuitable or unfavorable for agriculture (Table 2) ((Hammond, 1994; Trumbull, 1995) draw on work by (United Nations, 1993b)).

Table 1 Changes in land cover and use over the last 3 centuries

Land use type	Change in the last 300 years
Forest	1,100 million ha loss
Rangeland	2,000 million ha substantially degraded
Soils	1,200 million ha unable to support original ecosystems
Agriculture	Increase from 20 million to 15,000 million ha

Table 2 Global area of broad land cover classes (sources: (Hammond, 1994; Trumbull, 1995), (United Nations, 1993b))

Land use	Area (million hectares)	Area/person 1998 (ha)
Forest	3,900	0.67
Farm land	4,800	0.83
Other	4,341	0.75
Total	13,041	2.25

Under-nutrition remains a critical problem in LDCs. A report by the FAO (United Nations, 1993a) used land evaluation techniques to estimate future prospects for global food production, by combining data on soil quality, climate (temperature and moisture conditions) and terrain features. The study showed that in the last 30 years, per capita food supply had increased by 18%. The number of chronically undernourished people fell from 930 in 1973 to 800 million in 1993, or 23% of the global population in 1973 to 15% in 1993. By 2010, it is predicted that the number of chronically undernourished will fall further to 650 million or 9.3% of the global population, though FAO has recently set a more ambitious target of 400 million undernourished people. There were improvements in East Asia (a decrease from 250 to 70 million undernourished people) and Latin America; but sub-Saharan

[1] A population of 2 billion growing at 2% per year will add 40 million people per year, while a population of 5 billion growing at 2 % per year will add 100 million.

Africa has more than 300 million undernourished people and the situation is deteriorating.

An important development problem in less developed countries (LDCs) is to increase agricultural production in order to improve food supplies, generate income and employment, while simultaneously protecting the environment and nature conservation areas. LDCs are characterized by large workforces in the agricultural sector (for example 63% of the African labor force works in agriculture, and up to 90% in some African and Asian countries). Eliminating undernutrition is strongly connected to more rapid agricultural development, because the majority of the poor in less developed countries still depend on agriculture for food and income. Raising agricultural production requires the removal of resources constraints, including adequate water supply, identifying land suitable for different agricultural activities, developing high- yielding plant species, or improving agricultural practices (fertilization, herbicides, mechanical ground preparation, etc). Of these factors, water supply is critical, especially for irrigation. Remote sensing and GIS may contribute to many of these activities by providing data and derived information on a regional and local scale.

The provision, distribution and use of information dominate employment and economic activity in the developed economies. Precision agriculture, where detailed local-scale geographical and remote sensing information is applied to more precisely use fertilizers, herbicides and pesticides, promises to cut costs and increase production in developed countries. In the LDCs, remote sensing and spatial information may contribute to more efficient agricultural production through regional planning, land rehabilitation, and monitoring of land use changes such as conversion of forests to agricultural land. In the next section, the relationship between policy, participation in decision-making, and information is introduced.

Policy, participation and information

Three components are required for successful agricultural and natural resources management, namely policy, participation and information (Fig. 2). These factors are especially critical in less developed countries where infrastructure may be rudimentary. The balance between these three components will depend on the type of project as well as the infrastructure and the social, economic and cultural traditions of the country.
From Fig. 2, it can be seen that sustainable land use and development are based on:

* National, regional and local policy and leadership which may be asserted through diverse mechanisms including legislation, policy documents, imposing sanctions, introducing incentives (reduced tax, subsidies, etc.), motivation to contribute to development, and so on. Policy tools are necessary to encourage farmers and other natural resources managers to make good use of natural resources, and organize management in a sustainable manner.
* Participation by, and benefits to, local people (managers, landowners, stakeholders). If the local people directly benefit (through improved standard of living, better environment, gender equality, etc.) then they will contribute positively to the policy settings.
* An active non-government organization network to maintain accountability.

These elements require the provision of timely, accurate and detailed information on land resources. This spatial information is provided and applied through GIS and remote sensing. By integrating disciplines and technologies, better spatial information and maps will lead to improved planning, decision-making and hopefully generate harmony between production and conservation across a landscape.

The growth of GIS and remote sensing is explored in the next section. These technologies generate much of the information required for successful agro-ecological projects, and provide feedback for policy-makers, as well as local people who manage land.

Growth in GIS

Presently, there is a large demand for the products and services of the GIS industry, and GIS is undergoing tremendous growth (Table 3).

Table 3 Estimated growth in GIS sales and revenues

Year	Region	Annual % increase	Estimated value	Author
1990	Europe total sales	30	-	Green (1990)
1988	US total sales	28	635 million USD	Dataquest (1988)
1989	UK total sales	35	180 million GB pounds	Parker (1989)
1988	US total sales	32	529 million USD	Walker & Miller (1990)
1995	Global GIS software	13.7	563 million USD	Fairall (1995)
1994-98	Global software sales	27	-	Daratech (1998)
1994-98	Global total sales	18	-	Daratech (1998)

Another index of the growth in the spatial data industry is the number of new software packages released onto the market (Fig. 3). GIS and remote sensing activities are continuing to expand in response to regional and global environmental problems (*i.e.* rising populations and shrinking resources), as well as the demand from specialized marketing services and delivery of human services. Thus, GIS technology is a rapidly growing service sector industry, and remote sensing is a spatial data input to GIS.

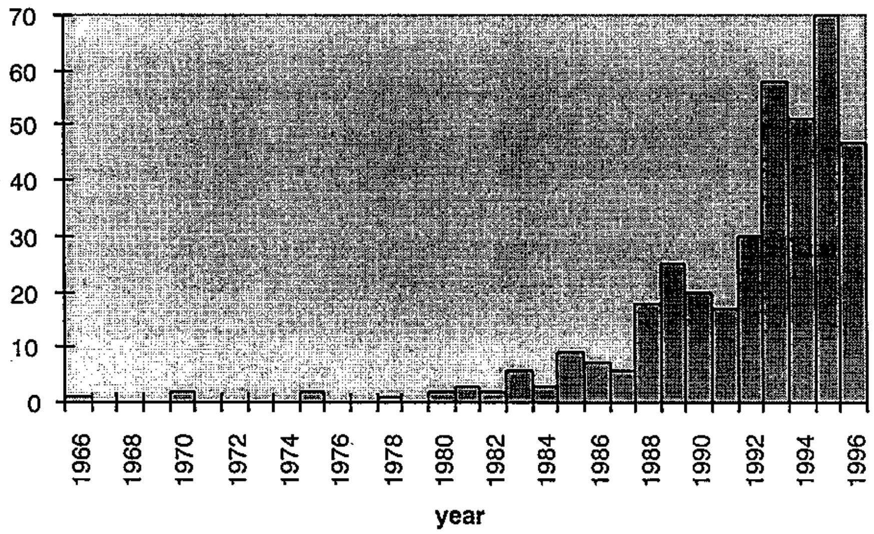

Fig. 3 Number of new software packages released onto the market (1970-1996)

The growth in GIS and remote sensing software is having a dramatic effect on the management of natural resources. In the next section, a number of successful remote sensing and GIS applications are presented.

Successful remote sensing and GIS applications

Aerial photographs are a mature and operational technology in fields as diverse as photogrammetry, forestry, agriculture, soil science, social sciences and geology. The main difference between aerial photography and digital imagery is that the interpretation is made by people using conventional photographs to identify objects and decide on their significance. With digital imagery, the enhancement, and often interpretation of objects, are undertaken using a computer.

Interpretation of aerial photographs remains a powerful tool for mapping and monitoring land cover and natural resources. The main advantage of using aerial photography is that it significantly reduces the time spent undertaking field work, along with making field work much more effective. Consequently, since the 1950s, aerial photographs have been enthusiastically used by professionals managing natural resources. Aerial photographs are relatively easy to obtain, flights can be arranged locally (and often on a short notice) when conditions are suitable, and photographs may be obtained on large scales. However, the cost of acquiring aerial photographs is high compared to satellite imagery, and a high labor input is required to compile and interpret a series of aerial photographs.

Two main techniques have emerged for mapping land resources. The land unit or land systems approach is a holistic method which identifies areas on aerial photographs or remotely sensed images with common properties, and assigns an attribute class to the area (Zonneveld, 1974; Zonneveld, 1988). It is a technique particularly suited to rapid survey in unmapped areas. In contrast, GIS and digital image processing of remotely sensed imagery is a reductionist approach, where the landscape is viewed as a series of separate data layers, which are combined in the computer to model environmental and agricultural features (Skidmore, 1989). The GIS approach is suitable for incorporating quantitative models based on existing map layers, plot measurements, as well as local knowledge (Turner and Baumer, 1984). Consequently, GIS has been rapidly adopted in well-mapped areas.

Satellite remote sensing is often the most up-to-date source of data and information for earth resources, and as indicated earlier, may be the only data available in developing countries. It is synoptic, allowing regional scale studies to be undertaken relatively quickly and cheaply, along with providing current information for updating maps or detecting change. It is possible to order satellite images over any portion of the earth surface from a number of different satellite systems[2].

A number of remote sensing systems provide data sets over a very long term (*e.g.* the US Landsat and NOAA AVHRR systems, as well as the French SPOT systems) which are proving invaluable for identifying change. The NOAA AVHRR is a particularly useful system, as twice daily images are available. Food early warning systems and estimated cereal production, based on NOAA AVHRR satellite data, have been developed by FAO in conjunction with national donor agencies in Africa (*e.g.* the ARTEMIS system). The changes in biomass over a season may be monitored and food shortages predicted. Such systems are operational in Kenya and West Africa, and used to predict food shortages, as well as projected national income from agriculture. New projects, using aircraft-based scanner to monitor the status of vegetation and crop biomass, are also being developed, as are applications to predict biodiversity.

The ability to access meteorological and NOAA AVHRR images in real time, as well as the archives of these images, has allowed land management agencies to track the development of major fires. The near infrared channels of the NOAA AVHRR have also been used to monitor the annual incidence of fires across Africa, and are routinely used to map fire development in Western Australia and the Northern Territory of Australia. An interesting application by NASA of the TOMS sensor designed to map ozone depletion, has been to monitor fire development.

Land evaluation can estimate the suitability of land for different uses by combining data on soil quality, climate (temperature and moisture conditions) and terrain features with remotely sensed data. These methods can be currently applied for land reform in southern African countries.

[2] Countries with remote sensing systems include France (SPOT), European Union, US (NOAA AVHRR, Landsat), Russia, India (IRS), Japan.

Techniques incorporating the values of local people have become important in development and conflict resolution. Such participatory approaches may be made more effective through the use of remote sensing to inform local people about the landscape in which they live. Participatory approaches are possible through the use of GIS to develop land use planning scenarios to highlight the effects of selecting different land management strategies, both from an individual perspective, as well as at a village or community level.

Using traditional scientific methods, local point-based data and associated models have become ubiquitous. An interesting development is how to scale up detailed point- based studies. A typical example includes estimates of pastoral and crop production, as well as wildlife habitat potential. Another type of point-based study is agricultural yield gap, where the actual production from a site does not match the potential production, for example as developed in experimental research stations. Such point-based studies may be extrapolated over large areas using GIS and remote sensing, in order to indicate to planners and farmers where production may be increased, and at what cost.

The environmental impact of development activities can be severe in countries undergoing rapid economic development, as planning controls may be poorly designed and policed. Environmental impact assessment and land use planning are based upon environmental profiles, which are geographical descriptions of a region of interest. Land use planning requires maps showing land capability for different purposes, as well as techniques to allocate land to different uses. It is a key factor in agricultural and nature conservation at a local and regional level, as it aims to select the best use of land, based on land capability and the needs of people. GIS and remote sensing provide a cheap, rapid and efficient method to generate the spatial information required for planning, impact assessment, and environmental profiles.

Table 4 The use of remote sensing by industry in the EU

Actual Use	Near-Actual Use	Some Use	Little or no Use
Oil and gas	Agri-industry	Fishing industry	Alternative energy
Land navigation	Transport and shipping	Forestry industry	Coal & mining
European Commission	Navigation industry	Water and utilities	Construction
Meteorological sector	Software	Public operations	Insurance
Agri-industry [3]	Travel/tourism/leisure	Public national admin.	Real industry
Insurance	Local & regional govt.	Non-government orgs.	News/media
Software	Intergovernment bodies		
Intergovernment bodies			
Travel/tourism/leisure			

Operational remote sensing systems in the EU were analyzed during a workshop held by the Centre for Earth Observation (CEO of the Space Applications Institute, Joint Research Centre, Rome) entitled "Has remote sensing found its customers?" The conclusions are summarized in Table 4[4]. Neil Hubbard *et al.* (1999) found that specific applications (*e.g.* precision farming) within broad market sectors (*e.g.* agri-industry) are becoming operational, but that broad economic segments cannot be categorized as operational or successful. The main markets with greatest potential within the next 5 years were identified as agri-industry, insurance, software, travel/tourism/leisure, intergovernmental bodies. In addition, other markets which have been most strongly purchasing imagery and using remote sensing included oil and gas, land navigation, the European Commission

[3] Italics refer to emerging or 'rising star' industries in the remote sensing field.

[4] Italics refer to emerging or 'rising star' industries.

and the meteorological sector.

It is clear that many sectors of the economy, including the agricultural and nature conservation sectors, still have somewhat limited use of remote sensing. The constraints to the uptake of GIS and remote sensing for agro-environmental issues in less developed regions are further explored in the next section.

Constraints to the application of GIS and remote sensing technology for agro-environmental issues in less developed regions

Satellite remote sensing has played a relatively minor role in the commercial success of GIS. There are a number of reasons for the poor uptake of remote sensing, but five appear to dominate. Firstly, the coarse spatial resolution of satellite images is fine for regional scale studies but most GIS analysis is on a local scale. Secondly, the primary data input into GIS has consisted of conventional cartographic maps in the form of vector data layers, which are expensive to convert to a digital (vector) format. High spatial resolution imagery will probably become the primary data model, along with providing the primary data source. Thirdly, there is a mismatch between the vector data structure (based on points, lines and polygons) used in GIS, and the raster (pixel)-based data structure used in remote sensing. There are difficulties in converting between these two data models. In addition, users have been conditioned to accept line work on maps as representing a boundary, when in fact most boundaries of natural resources features (such as soils, vegetation species mixes, or wildlife habitat suitability) are gradients. "Cartographic conditioning" results in most users delineating homogeneous areas (polygons) on maps, instead of mapping variables as a continuum, such as the density of a species, or the concentration of soil nutrients. The fourth reason for the slow uptake of remote sensing in GIS is poor accessibility to data due to the expense of higher resolution imagery, poor delivery systems for the data, or data being in the wrong format. This problem is particularly acute for environmental monitoring where budgets are often tight. Fifthly, there is a lack of expertise to extract information available in remotely sensed images.

A number of new satellite systems promise to deliver imagery that may improve our ability to map and monitor land resources. These are discussed in the next section.

New satellite remote sensing systems

New remote sensing systems will remove some of the above constraints and improve the utility of remotely sensed images for mapping and monitoring of land resources. Of most interest are the high spatial resolution satellite images, that are being developed by private sector companies, with a resolution of between 1 m and 3 m for panchromatic and multispectral imagery, respectively. The rapid acquisition of large-scale images will assist natural resource managers, particularly for monitoring purposes. Another advantage of high resolution imagery is that image resolution will better match the large scale used in most GIS analyses. In addition, overlapping pairs of images, will permit the generation of high accuracy digital elevation models. The imagery will be expensive - it is estimated that the cost will be approximately $US 30-50 per km^2, which is similar to aerial photography, but will be difficult for less developed countries to afford on a commercial basis.

High spectral resolution, or hyperspectral, imagery combines spatial imaging with a spectrometer. A spectrometer is a device which records up to several hundred narrow spectral bands with a spectral resolution of 10 nm or narrower. Unfortunately, broad band scanners tend to average out important differences in reflectance such as specific absorption pits. In addition, spectral ranges where the broad bands are placed may not coincide with the areas of maximum difference in the spectral curves for vegetation. There is a great potential for hyperspectral remote sensing in sustainable land management. Materials and cover types may be identified, permitting a vastly improved ability to map and monitor land cover and surface materials, monitor land degradation through changes in vegetation composition and structure, measure evapotranspiration and assess and monitor environmental degradation and fragmentation.

A third promising remote sensing image type is radar. The tone on a radar image relates to backscatter, with a light tone equivalent to strong backscatter. When the microwave interacts with the ground, it is scattered to varying degrees. Because objects depolarize radiation in different amounts, objects may be identified from their polarization. Since radar wavelength significantly affects the backscatter response of objects, characterization of objects based on wavelength is possible. Radar penetrates haze, smoke or cloud, and may be obtained regardless of weather of time of day (a major advantage in the "cloudy" northern latitudes, and the Tropics).

Integrating remote sensing and GIS

A number of studies have shown how remote sensing data and ancillary geographic data may be combined to improve the accuracy of maps, models and simulations (Aspinall and Veitch, 1993; Burrough, 1993; Hoffer and staff, 1975; Hoffer *et al.*, 1979; Lees and Ritman, 1990; Olsson, 1989; Rao and Reddy, 1993; Skidmore *et al.*, 1997; Zhou and Garner, 1990). The difference between image processing (of remotely sensed data) and analysis using geographic information systems becomes blurred when remotely sensed and other geographically registered data are merged in a (raster) GIS data model. There are many common processing techniques including geometric correction, cartographic output, and classification methods.

One processing technique which incorporates remote sensing and is executed in a GIS, is the expert system. Expert knowledge from farmers, agronomists, soil scientists, foresters, indigenous people or others interested in land resources management is an important (and sometimes the only) source of information. Participatory techniques have been adapted at ITC to extract information through interviews and discussion groups, particularly for land use planning. Expert systems can incorporate such knowledge into a GIS, and then automatically map areas and features of interest. An example is the Land Classification and Mapping Expert System (LCMES) (Skidmore *et al.*, 1997). Forest soils were mapped using terrain parameters, remote sensing and a knowledge base generated by interviewing soil scientists. Interestingly, there was no difference between the accuracy of the expert system map and a map prepared by a soil scientist. Expert systems retain the robustness of the scientific method, but allow knowledge and other "soft" data to be used in analysis, along with mapping more rapidly and with lower input of labor.

There is an increasing use of combining GIS and remote sensing to better visualize landscapes. For example, the impact of logging operations in a forested landscape may be visually assessed by draping an image of a forest on the three-dimensional landscape, and overlaying proposed logging compartments by draping images of logged areas also onto the three-dimensional landscape.

Conclusion

It is shown that there are a number of successful applications of remote sensing and GIS, developed in response to problems relating to agricultural production and nature conservation in the less developed regions. Some constraints to the development of remote sensing and GIS are explored. Solutions, including the integration of GIS and remote sensing, as well as the availability of new remote sensing systems, may overcome these constraints.

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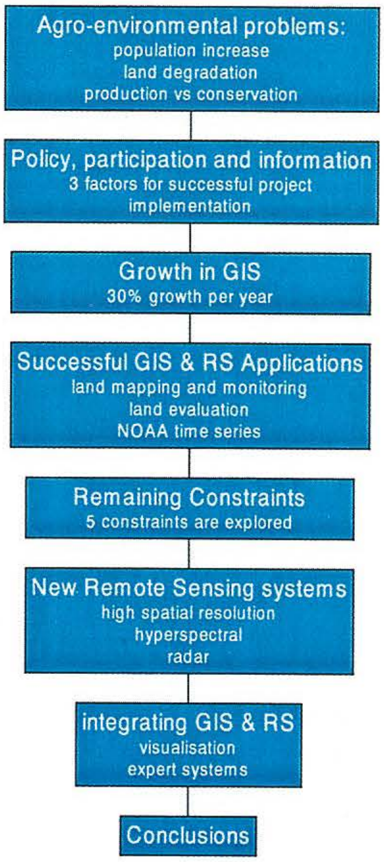

Fig. 1 Map of the presentation

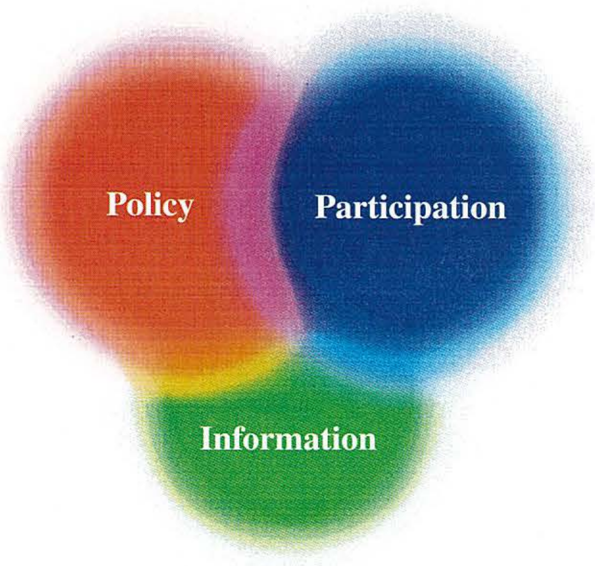

Fig. 2 Components necessary for a successful agro-ecological project - policy, participation and information