REMOTE SENSING AS A MEANS OF ECOLOGICAL INVESTIGATION

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ABSTRACT:

Much ecological analysis requires detailed spatial observation, traditionally conducted through field measurement. Remote sensing has been tested extensively as a means of ecological investigation, but many such studies were limited by the relatively coarse spatial resolution of the imagery used. The new generation of fine spatial resolution satellite sensors provides an opportunity for detailed and accurate ecological studies, reducing the need for expensive ground survey. This paper covers two main topics. First, the current status of the general field of ecological remote sensing is described, with particular reference to recent developments in spaceborne data availability. Second, specific research findings related to habitat monitoring in southern Africa are presented. Vegetation distributions are investigated at a range of spatial and temporal scales using various sources of remotely sensed data. The vegetation information is then integrated with animal population data to further our understanding of the dynamic relationship between the two.

1. INTRODUCTION

Ecology is 'the scientific study of the interactions between organisms and their environment' (Begon *et al.* 1990, p. x). Ecological investigation undertakes to understand, describe, predict and control these organisms. Generally, such investigation requires spatially explicit data, given the fundamental need for knowledge about the location and distribution of species (Turner *et al.* 2003). The traditional means of collecting ecological data is through manual, field-based observation. This approach has the benefit of generating highly accurate measurements, but, due to its labour-intensive nature, it is generally impractical for anything other than local scale studies. The implications of ecological analysis, though, extend well beyond the local scale, and there is considerable need for, and interest in, ecological investigation at wider spatial scales, from the 'landscape' (Gulinck *et al.* 2000) to the entire globe (Los *et al.* 2002). Consequently, remote sensing has become common in much ecological investigation, providing the only realistic, cost-effective means of acquiring data over large areas (Nagendra 2001, Kerr and Ostrovsky 2003).

While remote sensing has become a key mechanism for generating ecological data, certain limitations exist regarding the spatial detail of these data. Notably, until recently, the spatial resolution of spaceborne remotely sensed imagery was 'far too coarse to detect most organisms' (Turner *et al.* 2003, p. 306), preventing detailed ecological analysis. Specifically, ecologists were restricted largely to 10 m and 20 m spatial resolution imagery (panchromatic and multispectral, respectively) from the Systeme Pour l'Observation de la Terre (SPOT) satellite's High Resolution Visible (HRV) sensor, 30 m spatial resolution imagery from Landsat's Thematic Mapper (TM), and other coarser spatial resolution imagery (e.g., Franklin *et al.* 1994, Luque 2000). However, given that 'many phenomena of interest to ecologists… occur over large extents but at local scales' (Read *et al.* 2003, p. 592), the level of spatial detail provided by SPOT HRV or Landsat TM imagery is likely to be insufficient for much ecological investigation.

Recently, a new generation of fine spatial resolution satellite sensors has emerged (Van der Meer *et al.* 2002, Aplin 2003a), capable of providing imagery with a level of detail that may be sufficient for meaningful and accurate local scale ecological investigation (de Leeuw *et al.* 2002, Clark *et al.* 2004b). In particular, imagery with a spatial resolution of 1 m (panchromatic) and 4 m (multispectral) or finer is available from instruments such as IKONOS and QuickBird (Sawaya *et al.* 2003). Given that these 'observations are at a spatial scale equivalent to field measurements typically carried out in ecological and land cover research' (Goward *et al.* 2003, p. 80), the implications for ecological investigation are significant.

This paper reviews the general field of ecological remote sensing, with particular reference to recent developments in fine spatial resolution satellite sensors, and presents ongoing habitat monitoring research in southern Africa. Initially, remote sensing-based ecological investigation is introduced generally, followed by a discussion on the ecological implications of fine spatial resolution imagery. Next, African applications of ecological remote sensing are described, leading finally to a summary of ongoing habitat monitoring research in Kruger National Park, South Africa.

2. REMOTE SENSING AND ECOLOGY

The relationship between remote sensing and ecology is not particularly well-defined and is almost certainly under-exploited (Gulinck *et al.* 2000). A mismatch in aspirations and practices seems to exist between the two disciplines, preventing close integration. Ecologists, in general, seem reluctant to adopt new approaches, particularly involving observation at, from their viewpoint, relatively coarse spatial scales (Turner *et al.* 2003). Remote sensing specialists, for their part, have perhaps focused on technological issues as their principal concern, rather than ecological problems. Closer integration, likely involving creativity and compromise, may benefit both disciplines.

Despite the basic divergence between remote sensing and ecology, there are many successful examples of ecological remote sensing applications. Turner *et al.* (2003) describe the distinction between direct and indirect approaches, also referred to by Nagendra (2001). Direct ecological remote sensing involves, fairly obviously, direct observation of vegetation categories and even animal populations (Sidle *et al.* 2002) from remotely sensed images. Indirect ecological remote sensing involves the derivation of environmental parameters from remotely sensed images as proxies for ecological phenomena (de Leeuw *et al.* 2002). Commonly, for instance, habitats are derived from vegetation categories to infer the distribution of animal populations.

Kerr and Ostrovsky (2003) describe three main areas of ecological remote sensing. First, simple land cover classification is useful for straightforward identification of vegetation types and derivation of habitats. Second, integrated ecosystem measurements are invaluable in providing estimates of ecosystem function over large areas (entire ecosystems). In particular, there has been considerable recent interest in using remote sensing to derive biophysical parameters such as leaf area index (LAI) and net primary productivity (NPP), sometimes using normalised difference vegetation indices (NDVI) (Goetz 2002). Third, change detection is essential for ecological monitoring and, given the continuous and stable nature of spaceborne image acquisition, remote sensing provides an excellent source of data for this purpose (Coppin *et al.* 2004). Further, such temporal analysis can be extrapolated to predict future ecological change, for instance to estimate the result of anthropogenic land use practices on protected species.

While most ecological remote sensing involves the use of optical (multispectral, and to a lesser extent, panchromatic) imagery, various other image types are used. The recent emergence of hyperspectral imagery is particularly relevant here, given the ability of this fine spectral resolution imagery to detect subtle differences between highly specific land cover classes, typically vegetation categories or soil types (Turner *et al.* 2003). Another emerging technology, lidar (light detection and ranging), is particularly useful for measuring height (Van der Meer *et al.* 2002), which may then be incorporated in further ecological analysis. Finally, radar imagery has been used relatively widely for ecological investigation, and Kasischke *et al.* (1997) describe four main applications: (i) land cover classification, (ii) woody plant biomass estimation, (iii) flood analysis and (iv) temporal monitoring.

3. FINE SPATIAL RESOLUTION SPACEBORNE IMAGERY

For much of its history, spaceborne remote sensing has been constrained by technological limitations, and also by governmental legislation. Specifically, during the Cold War, the USA and Russian militaries restricted public access to fine spatial resolution imagery. Given rapid technological development and relaxing legislation when the Cold War ended, various private and governmental organisations became engaged in developing fine spatial resolution satellite sensors by the mid 1990. Further, the imagery from these instruments was intended for general public use, rather than being restricted to the military (Aplin *et al.* 1997, Birk *et al.* 2003). (For convenience, here, ‘fine spatial resolution imagery’ is defined as imagery finer than the 10 m spatial resolution SPOT HRV imagery (which was already available at the time the new sensors were developed).)

Various fine spatial resolution satellite sensors have now been developed (Table 1), and others are planned for development. The first instrument to be operational was the 5.8 m spatial resolution panchromatic sensor on board the Indian Remote Sensing Satellite (IRS)-1C, launched in 1995. A successor, IRS-1D, was launched two years later, with a slightly finer (5.2 m) spatial resolution. The most well-known of the fine spatial resolution satellite sensors, and regarded widely as the first of this new ‘era’ of remote sensing, is IKONOS, launched in 1999. (The IRS instruments had received little attention in large parts of the world, notably the USA. Indeed, IKONOS, comprising 1 m and 4 m sensors (panchromatic and multispectral, respectively) (Dial *et al.* 2003), does have markedly more advanced technology that the IRS instruments.) In 2000, EROS-A1 was launched with a 1 m spatial resolution panchromatic sensor, although this Saudi Arabia-based enterprise has also received relatively little attention in the USA and elsewhere. A significant event occurred in 2001, with the launch of QuickBird, comprising the finest spatial resolution imagery available currently (0.61 m and 2.44 m spatial resolution panchromatic and multispectral imagery, respectively). Since then, the latest SPOT satellite has been launched, including more advanced instruments than previous SPOT missions (two panchromatic sensors with spatial resolutions of 2.5 m and 5 m respectively, and a 10 m spatial resolution multispectral sensor), and, finally, OrbView-3 was launched in 2003, with instruments similar to IKONOS.

Year of launch	**Satellite sensor**	**Spatial resolution (m)**	
		Panchromatic	Multispectral
1995	IRS-1C	5.8	
1997	IRS-1D	5.2	
1999	IKONOS	1	4
2000	Eros-A1	1	
2001	QuickBird	0.61	2.44
2002	SPOT HRG	2.5, 5	10
2003	OrbView-3	1	4

Table 1. Fine spatial resolution satellite sensors (IRS = Indian Remote Sensing Satellite, SPOT = Systeme Pour l’Observation de la Terre, HRG = High Resolution Geometry.)

Fine spatial resolution satellite sensor imagery has been used for a range of ecological applications. There has been considerable interest in forest analysis and, in fact, some of the earliest published examples of IKONOS data exploitation related to woodland. For instance, Franklin *et al.* (2001) demonstrated the value of texture measures derived from panchromatic IKONOS imagery for distinguishing forest age classes. Other studies have focused on tropical forests, and IKONOS and QuickBird data have been demonstrated as an accurate means of studying forest demographics (Clark *et al.* 2004a), structure and dynamics (Read *et al.* 2003). However, not all ecological investigation is focused on rural areas, and IKONOS imagery has been used to aid certain urban analyses. Greenhill *et al.* (2003), for instance, describe the benefit of multispectral IKONOS imagery in determining the ecological characteristics of suburban land. There has also been extensive use of IKONOS imagery in hydrological applications such as watershed management (Hall *et al.* 2004), and marine applications like coral reef classification (Andréfouet *et al.* 2003).

The benefit of fine spatial resolution imagery over coarse spatial resolution imagery for ecological investigation is fairly obvious. Generally, as spatial resolution increases (becomes finer), the accuracy with which small objects are identified and characterised increases. Indeed, there are various examples of studies where fine spatial resolution imagery has been compared favourably to coarser spatial resolution imagery. For instance, IKONOS imagery has been found to be more accurate than SPOT HRV and Landsat Enhanced Thematic Mapper Plus (ETM+) imagery for monitoring forest storm damage (Schwarz *et al.* 2003) and mapping coral reefs (Capolsini *et al.* 2003). However, fine spatial resolution imagery is not always appropriate for ecological studies. Hochberg and Atkinson (2003) found IKONOS imagery less accurate than hyperspectral imagery for distinguishing coral, algae and sand, and Asner *et al.* (2002) concluded that IKONOS imagery was insufficient for accurate estimation of tree crown dimensions. Further, Sawaya *et al.* (2003) demonstrated IKONOS and QuickBird imagery to be useful for resource management, but suggest that these data are uneconomic for large area studies.

It should be noted that airborne remote sensing may be a suitable alternative to fine spatial resolution spaceborne imagery, given that the relatively low altitude of airborne platforms enables the generation of very fine spatial resolution data. However, airborne remote sensing is limited in that data are acquired on a piecemeal basis (compared to continuous satellite sensor image acquisition), they may be expensive and they are particularly susceptible to geometric distortion (Goetz *et al*. 2003). Overall, the key factor determining successful applications in ecological remote sensing, and in remote sensing in general, is to match project goals to technical capabilities (Sawaya *et al.* 2003). Therefore, the level of detail required in any individual study will determine whether or not fine spatial resolution imagery is required. Sometimes, fine spatial resolution imagery may be useful only as a supporting data source, in combination with other resources (Quinton *et al.* 2003). For instance, Palandro *et al.* (2003) describe the use of IKONOS imagery to assess the accuracy of Landsat TM and ETM+ image classification.

4. AFRICAN APPLICATIONS

Fine spatial resolution spaceborne imagery has been tested fairly extensively for a range of ecological analyses in North America, for tropical forest studies in South America and for coral reef projects at locations throughout the world. However, relatively little such work has been conducted throughout Africa. Thenkabail (2004) describes a major study conducted in Nigeria, Benin and Cameroon to compare the capabilities of IKONOS and Landsat ETM+ imagery for representing rainforest and savanna ecoregions. NDVI analysis was used to determine the vegetal component of a range of land cover classes and ecological units. Thenkabail (2004) concludes that IKONOS data provide a more detailed depiction of vegetation and related factors such as biomass than Landsat ETM+ data. This is due partly to the finer spatial resolution of IKONOS, and partly to the greater (11 bit) dynamic range of IKONOS data than (8 bit) Landsat ETM+ data. In another project, Thenkabail *et al.* (2004) conduct an exhaustive comparison between IKONOS imagery and various other sources of multispectral and hyperspectral imagery for calculating rainforest biomass in Cameroon. In this case, IKONOS and the other multispectral data sources were markedly less accurate than hyperspectral Hyperion imagery.

In a Zambian study, IKONOS imagery has been processed to define LAI and forest canopy roughness, used in a wider experiment to monitor energy fluxes between vegetation and the atmosphere (Scanlon and Albertson 2003). Elsewhere in Zambia, Hansen *et al.* (2002) describe the use of IKONOS imagery to generate an accurate tree crown cover map, used to validate a global percent tree cover data set, generated by the Moderate Resolution Imaging Spectroradiometer (MODIS). In fact, IKONOS imagery is conducted for MODIS validation elsewhere in Africa, including Botswana (Morisette *et al.* 2003).

4. HABITAT MONITORING IN SOUTHERN AFRICA

Kruger National Park (KNP) represents a managed, semi-natural environment. The park operates as a preserve for endemic flora and fauna, and is a major visitor attraction. It is believed that management practices throughout the twentieth century have fundamentally altered vegetation distribution throughout the park (Van Wilgen *et al*., 1998). In particular, numerous artificial water resources were created to attract wildlife to specific locations for viewing by tourists. The increased water resources may have led to an overall increase in vegetation abundance, and may be contributing to structural homogenisation of the park's vegetation (Eckhardt *et al*., 2000. Related processes include infestation of alien plant species and dramatic growth in certain animal populations, notably elephant and rhinoceros (Figure 1).

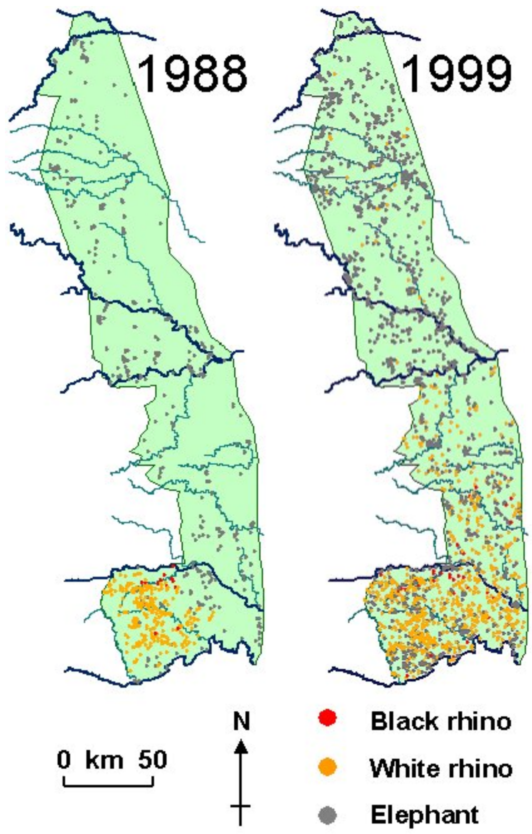

Figure 1. Recent growth in large herbivore distributions in Kruger National Park.

There is a strong need for accurate ecological monitoring in KNP to inform management practices, thereby maintaining biodiversity. Remote sensing provides an excellent source of data for such ecological investigation and, in fact, has long been used within KNP for this purpose. A rich remote sensing (and associated geographical information system) data resource is available for the park, including images from Landsat, SPOT, IKONOS and QuickBird instruments, and numerous airborne images and photographs (Aplin 2003b).

The strengths of fine spatial resolution satellite sensor imagery for ecological studies have been described above. In simple terms, fine spatial resolution imagery such as QuickBird enables more detailed observation than coarser spatial resolution imagery such as Landsat ETM+. For instance, while individual trees and even airport runway markings can be identified using a 2.8 m spatial resolution QuickBird image, the runway and service road can barely be discerned using a 30 m spatial resolution Landsat ETM+ image (Figure 2). In ecological terms, QuickBird provides the benefit of observing at the individual plant level, while Landsat ETM+ enables only aggregated measurements of vegetation (or other land cover) patches.

(a)

(b)

Figure 2. Skukuza airport runway, Kruger National Park, showing the finer feature delineation provided by (a) 2.8 m spatial resolution QuickBird imagery compared to (b) 30 m spatial resolution Landsat Enhanced Thematic Mapper Plus imagery. (North is to the top of the page and the image extends approximately 1 km east-west.)

In KNP, fine spatial resolution satellite sensor imagery has application for each of the three main areas of ecological remote sensing outlined by Kerr and Ostrovsky (2003): land cover classification, integrated ecosystem measurement and change detection. Both IKONOS and QuickBird imagery are available for analysis, although these data are usefully combined with coarser spatial resolution imagery to extend analysis over relatively large areas. For instance, spatially detailed QuickBird data can be linked to, and extrapolated over the wider areal coverage of, Landsat ETM+ data.

Examples of fine spatial resolution image analysis are provided in Figure 3. Specifically, a 2.8 m spatial resolution multispectral QuickBird image, acquired on 15 November 2002, was atmospherically corrected using dark object subtraction and geometrically registered to the local map projection system. (Figure 3a). Cloud and cloud shadow, prevalent in the image, were then masked out, before simple land cover classification was performed (Figure 3b) to gain an understanding of the spectral separability of classes, particularly vegetation types. Sometimes, though, fine spatial resolution imagery can be too detailed for accurate classification analysis, particularly in very mixed semi-natural environments such as KNP. For instance, where pixel size (e.g., 2.8 m spatial resolution QuickBird imagery) is markedly smaller than features of interest (e.g., 10 m tree canopies), classification algorithms may erroneously classify within-feature variation (Aplin *et al.* 1999). The key consideration here is to select classes with regard to the discriminatory capabilities of the spatial resolution of the data, and/or vice versa.

A technique that makes full use of the detail present in fine spatial resolution imagery (sometimes used in combination with, or as an input to, classification) is texture (Figure 3c). Texture measures, of which there are many, exploit the spatial variation between pixels, enabling features or areas to be characterised according to how homogeneous or heterogeneous they are. For instance, while tree canopies or parts of tree canopies may be misclassified using land cover classification, they may have characteristic (smooth or rough) textures, enabling accurate identification.

Given the difficulties of allocating pixels to specific land cover classes in mixed environments like KNP, it can be useful to use continuous rather than thematic representations. A common means of characterising the presence of vegetation, for instance, is through NDVI analysis (Figure 3d). This has the benefit that pixels are not forced into (sometimes inappropriate) classes, but instead provide a proportional measure of vegetation. Further, analyses such as NDVI can contribute to the derivation of biophysical variables such as LAI and NPP.

Finally, habitat monitoring can be performed by comparing analyses such as land cover classification and NDVI over time. Aplin (2003b) provides an example of vegetation change analysis in KNP conducted using Landsat ETM+ imagery. Research remains ongoing to exploit fine spatial resolution satellite sensor imagery, in combination with coarser spatial resolution imagery, for ecological investigation in KNP. In particular, vegetation information derived from remote sensing is integrated with animal population data to further our understanding of the dynamic relationship between the two.

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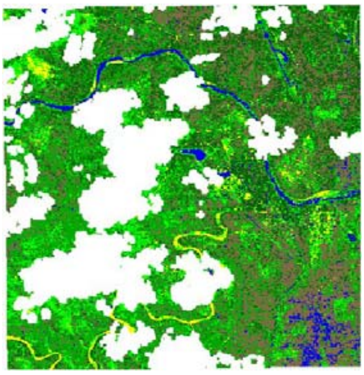
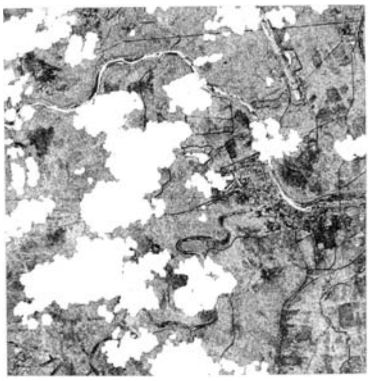
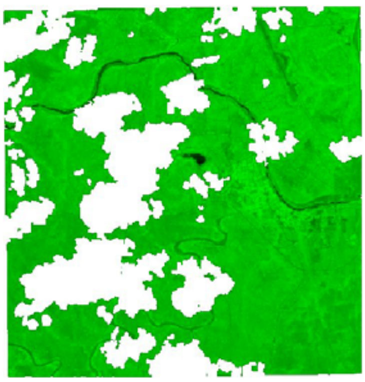
(a)



(b)



(c)



(d)

Figure 3. QuickBird image of Skukuza and surroundings, Kruger National Park: (a) false colour composite, (b) land cover classification, (c) texture and (d) normalised difference vegetation index. (North is to the top of the page and the image extends approximately 8 km east-west.)

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