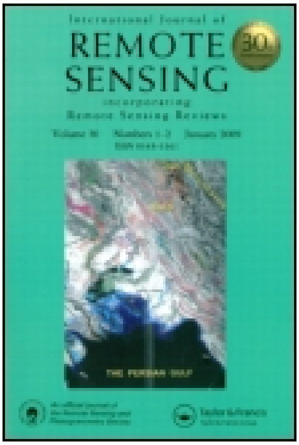

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Potential of colour-infrared digital camera imagery for inventory and mapping of alien plant invasions in South African shrublands

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Potential of colour-infrared digital camera imagery for inventory and mapping of alien plant invasions in South African shrublands

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Abstract. Australian *Acacia* plant species invade the fynbos biome of southern Africa and threaten the exceptionally high plant diversity in the Cape Floristic Region. We examine the utility of very-high spatial resolution (0.5 m) colour infrared (CIR) digital image data for discriminating *Acacia* species from native fynbos vegetation, other alien vegetation and bare ground. Image data were acquired at a very low cost with a single-chip, digital CIR camera mounted on a light aircraft. Shrub and tree features were uniquely identified using visual or computer-assisted interpretation. However, increases in dynamic range and accuracy of interpolation schemes for the single chip sensor will be required if semi-automatic and accurate mapping of invasive plants is to be achieved.

1. Introduction and background

Non-native plants can spread to invade endemic ecosystems, often threatening native biodiversity (Cowling *et al.* 1992). Such invasions have influenced resource managers to seek information on the extent, density and spread of alien plants. Remote sensing is required to map spatial distributions of alien plants and monitor their changes over time in an efficient manner. The requirement for large area coverage with sufficiently high spatial resolution to identify woody alien plants, at a relatively low cost, presents a major challenge to any data collection approach.

Much of the shrubland vegetation of the Cape Floristic Region of South Africa (called fynbos) has been invaded by alien plants (Richardson *et al.* 1992). The main invaders in lowland parts of this region are several species of *Acacia*, especially *A. cyclops*, *A. saligna* and *A. mearnsii*. *Acacia* trees and shrubs are generally larger than the native fynbos species. Since Acacia invasions in the lowlands range from scattered individuals to large dense patches, several types of remote sensing imagery may be required for efficient mapping of the extent and density of these alien plants.

The objective of this Letter is to examine the utility of digital colour infrared (CIR) imagery, acquired with an airborne, single-chip digital camera system, for economically identifying *Acacia* plants in the Cape lowlands. The low cost of the imaging system and imagery acquisition, along with the very high spatial resolution and CIR capabilities would seem to be attractive for identifying individual plants of

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the three *Acacia* species in locations where they have just begun to spread into native fynbos. Such locations are high priority zones for clearing of alien plants. Imagery acquired with a Kodak Model DCS 420 CIR digital camera mounted on a small, fixed-wing aircraft was evaluated for this purpose. The spectral-radiometric separability of the *Acacia* plants relative to the natural vegetation and developed land cover backgrounds is examined in the context of inventorying these alien plants.

2. Methods

2.1. *Imaging system*

Digital images were captured with the DCS 420 CIR digital camera which is based on a single, charge coupled device (CCD) (Light 1996) framing array composed of 1536 pixels by 1024 pixels. A lap-top computer controlled image acquisition and storage, and enabled previewing of images and histograms while in flight. A customized camera mount was built and bracketed to a door of a high-wing aircraft, such that the field-of-view of the camera was nadir looking.

The DCS 420 camera was operated in the CIR mode, such that every two-by-two pixels of the CCD array consist of two pixels that are sensitive to green, one to red and one pixel to near infrared (NIR) radiance. The green and red sensitive pixels are also sensitive to NIR radiance. Two software operations are required to generate a continuous, false CIR composite digital image, (1) interpolation and (2) subtraction of the NIR contribution to the green and red digital number values (i.e. spectral decomposition). The software driver for the DCS 420 converts raw image values into a three-band CIR image data set through a multiple step algorithm that includes convolution operators and is designed to reproduce the visual appearance as Kodak CIR aerial film products.

2.2. *Image acquisition*

Digital CIR image frames were acquired along major roads throughout the West Coastal Plain of the Cape Province of South Africa from 30 April to 2 May 1997. Orienting flightlines along roads enabled the pilot to navigate in the absence of global positioning or inertial navigation systems on the aircraft. Roads also provided convenient access for field reconnaissance in support of image analyses. A variety of alien plant types and distributions and landcover backgrounds were captured. Image frames were acquired at 10 second intervals along the flightlines with a ground speed of 40 m s^{-1} which resulted in 400 m between exposure stations. Each frame covered an area 750 m across track by 500 m along track. Three image frames were selected for analysis in this Letter. They were captured between 14:30 hrs and 15:45 hrs on 30 April 1997 from an altitude of 1000 m above ground level, which yielded images with a nominal ground sampling distance (GSD) of 0.5 m.

2.3. *Image processing and analysis*

Based on research into the DCS spectral decomposition and spatial interpolation routines developed by Kodak, a decision was made to develop and apply a custom pre-processing routine. Weighting factors for removing the NIR radiance component from the raw green and red values were derived from laboratory images captured over the exit aperture of an integrating sphere with known radiance output. Directly-sensed DN values for the NIR waveband were interpolated and interpolated NIR values were multiplied by the green or red band weighting factor. The resultant products were subtracted from the raw green and red DN-values. The spectrally decomposed green and red values were then interpolated to generate complete multispectral image arrays. Simple, linear interpolation was implemented based on the two nearest pixels for red and NIR wavebands and the four nearest pixels for the green band. A vignette correction mask was derived by averaging multiple images of the uniform irradiance field from the integrating sphere and applied to each image frame (Stow *et al.* 1996).

Hard copy prints of false CIR composite images were generated and used for field reconnaissance purposes (figure 1). Field annotations on the image prints were utilized for subsequent spectral signature evaluation and image classification.

Spectral signatures were extracted for *A. cyclops*, *A. saligna*, several species of *Eucalyptus* trees, patches of native fynbos shrub vegetation, individual fynbos shrubs of larger stature (e.g. *Euclea* and *Rhus spp.*), and bare soil (mostly sandy texture). Pixels were sampled separately from illuminated, shaded and shadow portions of trees and large shrubs.

An unsupervised, per-pixel classification was implemented to determine if unique and consistent signatures were inherent for the *Acacia* plants relative to other vegetation and the soil background. An ISODATA clustering routine was run with 50 cluster classes and clustering parameters were adjusted iteratively (Phinn *et al.* 1996). Cluster classes were visually labelled into information classes based partly on the annotated DCS-CIR hard copy images. Pixels corresponding to cluster classes identified as illuminated canopies of shrub or tree forms were masked and then subjected to a second clustering with 30 cluster classes.

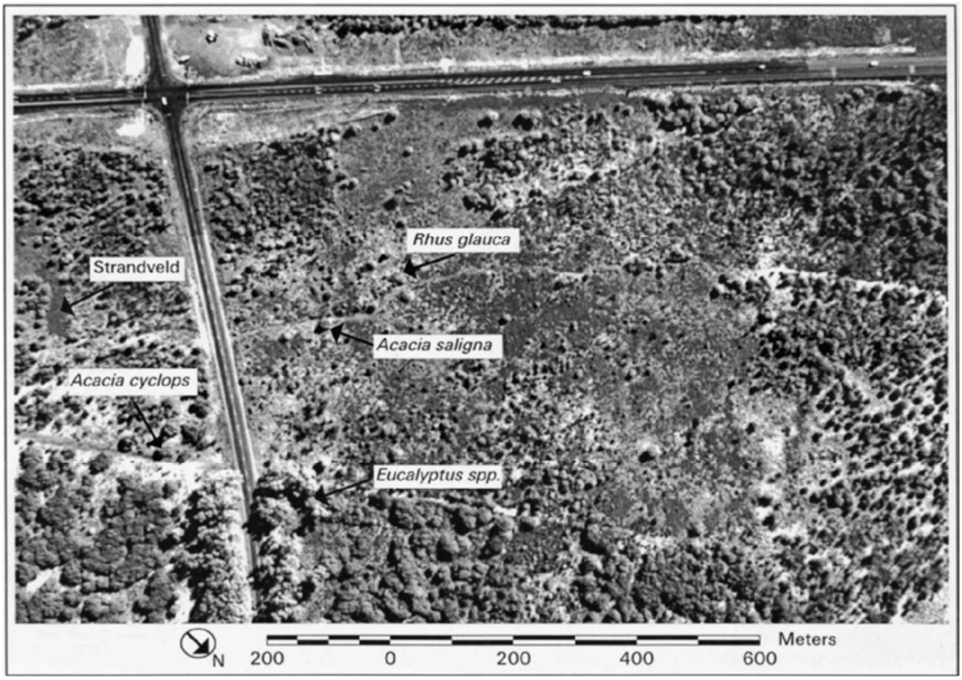

Figure 1. Single frame, near infrared waveband image derived from the Kodak DCS for an urban-rural fringe area of West Coastal Plain (north of Cape Town) acquired 30 April 1997.

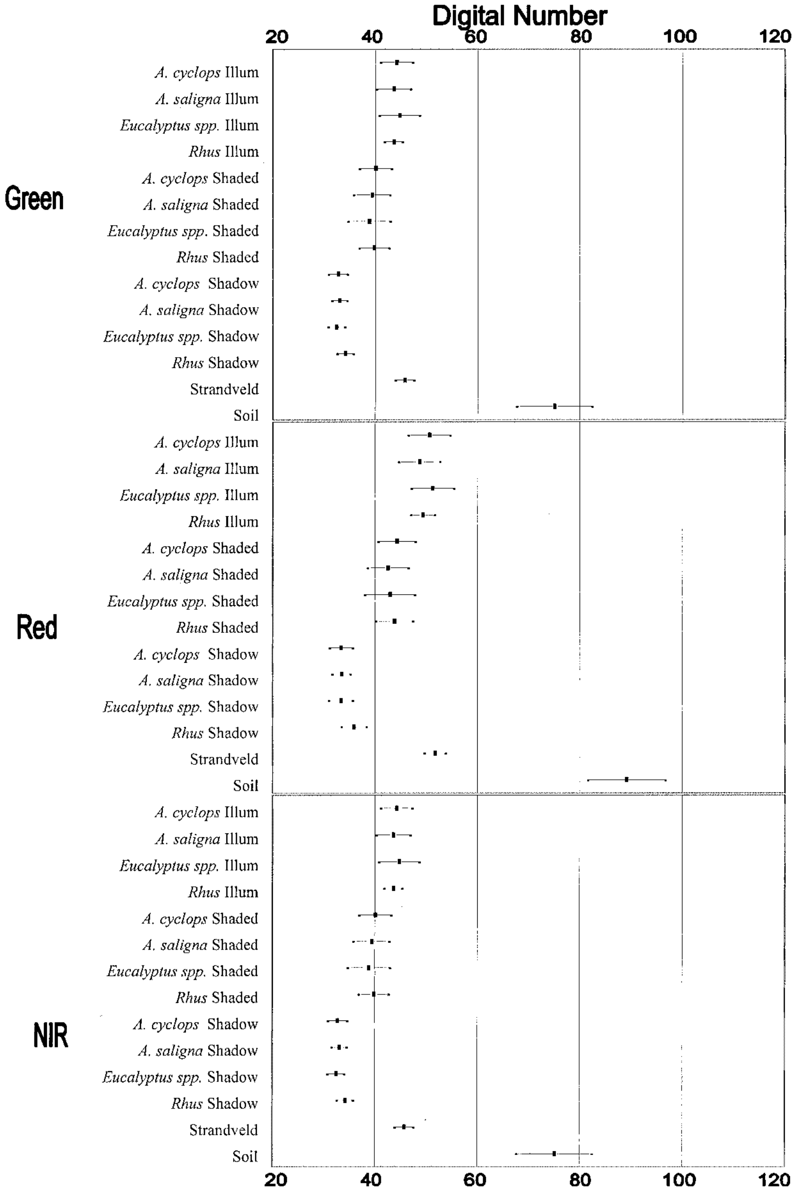

Figure 2. Coincident spectral plot illustrating spectral signatures as Green, Red, and Near-infrared digital numbers for illuminated and shaded canopies and shadows of dominant native and alien vegetation and bare soil samples.

3. Results and conclusions

Following the image interpolation and spectral decomposition processing, the visual quality of the resultant digital camera imagery was deemed high and the radiometric fidelity fair. The dynamic ranges of the post-processed image frames used for this study were slightly less than 128 DN values, or nearly the equivalent of 7-bit quantization for all three bands. The full 8-bit range is unattainable with this single-chip camera, given that green and red sensitive pixels have almost equal

Table 1. Matrix of Transformed Divergence values of spectral separability (all bands combined) for illuminated shrubs and trees, strandveld vegetation, and bare soil. Numbers correspond to replicate training sites: c = *Acacia cyclops*, e = *Eucalyptus* spp., r = *Rhus*, sal = *Acacia saligna*, str = Strandveld. Values of 2000 represent complete signature separability, with discrimination between pairs of samples less likely with decreasing transformed divergence values.

	c1	c2	c3	e1	e2	e3	r1	r2	r3	sal1	sal2	sal3	soil1	soil2	soil3	str1	str2	str3
c1	----																	
c2	**1927**	----																
c3	**979**	**1859**	----															
e1	1982	1046	1994	----														
e2	1997	1755	2000	**1490**	----													
e3	1852	429	1877	**654**	**1047**	----												
r1	1498	1999	1977	2000	2000	1988	----											
r2	417	1764	1064	1914	1989	1677	**1791**	----										
r3	1765	2000	1998	2000	2000	1999	**741**	**1839**	----									
sal1	1424	1009	1766	1128	1878	847	1968	1209	1999	----								
sal2	1730	1261	1799	1353	1929	1278	1997	1300	1999	**1264**	----							
sal3	1971	1417	1979	1461	608	1060	1998	1925	2000	**1817**	**1691**	----						
soil1	2000	1999	2000	2000	2000	1996	2000	2000	2000	2000	2000	2000	----					
soil2	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	**1976**	----				
soil3	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	**1371**	**1609**	----			
str1	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	----		
str2	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	**1078**	----	
str3	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	**803**	**580**	----

sensitivity to NIR radiance; to maximize the dynamic range of NIR would result in a saturation of green and red band images. Shrubs and trees as small as 1.5 m in diameter were discernible, as were road stripes on two-lane highways. Subtle differences in the shape of plant canopies were not recognizable. The relatively large solar zenith angles ($\theta = 50–60°$) during the afternoon acquisition period aided differentiation of life form types by their structural (e.g. height) characteristics. This accentuated differences in alien shrubs and trees, relative to native shrubs and other alien trees such as *Eucalyptus*. However, the shape of *A. cyclops* and *saligna* canopies are not consistently characteristic to enable visual or automatic recognition.

Spectral signatures for native and alien plants, shadowed ground and illuminated soil derived by pooling DN values from at least five replicate features are shown in figure 2. For the shrub and tree forms captured at very-high spatial resolution, the largest variations in image brightness are associated with differential illumination across a given plant canopy, rather than between species variations in canopy spectral signatures.

Transformed Divergence measures of signature separability for three replicates of illuminated canopies of tree forms, native shrub and strandveld vegetation, and bare soil are presented in table 1. The NIR signatures of the illuminated canopies for the *Acacia* species are weakly separable during the autumn season, as were the illuminated canopies of *A. saligna* relative to native thicket and shrub vegetation, and alien *Eucalyptus* trees. Some signature overlap in all three bands is evident for *A. cyclops* relative to native shrubs such as *Euclea* and *Rhus*.

Unsupervised, per-pixel classification results exihibited substantial within canopy heterogeneity in cluster classes. Illuminated *Acacia* plants consistently occurred as contiguous blocks of a few distinct cluster classes. Pixels associated with non-*Acacia* canopies most commonly had no membership in these cluster classes.

For high spatial resolution imagery, an object based or multiple-pixel feature classification approach is likely required to identify alien plants that occur as isolated plants. Image segmentation could be initially implemented, with large plant life forms identified by a sequence of illuminated canopy, shaded canopy and shadow (Warner *et al.* 1998). Knowledge of the solar principal plane direction could be incorporated to recognize this characteristic sequence of canopy elements to discriminate trees from other life forms. Genus, or even species-level identification could be based on isolating pixels corresponding to directly illuminated portions of the canopy and classifying the multi-pixel objects based on the spectral-radiometric signatures of those pixels.

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