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Evaluation of vegetation indices for assessing vegetation cover in southern arid lands in South Australia

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Abstract. Vegetation indices are widely used for assessing and monitoring ecological variables such as vegetation cover, above-ground biomass and leaf area index. This study reviewed and evaluated different groups of vegetation indices for estimating vegetation cover in southern rangelands in South Australia. Slope-based, distance-based, orthogonal transformation and plant-water sensitive vegetation indices were calculated from Landsat thematic mapper (TM) image data and compared with vegetation cover estimates at monitoring points made during Pastoral Lease assessments. Relationships between various vegetation indices and vegetation cover were compared using simple linear regression at two different scales: within two contrasting land systems and across broader regional landscapes. Of the vegetation indices evaluated, stress related vegetation indices using red, near-infrared and mid-infrared TM bands consistently showed significant relationships with vegetation cover at both land system and landscape scales. Estimation of vegetation cover was more accurate within land systems than across broader regions. Total perennial and ephemeral plant cover was best predicted within land systems, while combined vegetation, plant litter and soil cryptogam crust cover was best predicted at landscape scale. These results provide a strong foundation for use of vegetation indices as an adjunct to field methods for assessing vegetation cover in southern Australia.

Additional keywords: arid environment, Landsat TM, rangelands.

Introduction

Vegetation cover has been widely recognised as one of the best indicators for determining land condition (Booth and Tueller 2003; Bastin and Ludwig 2006; Wallace *et al*. 2006). Consequently, land condition is often assessed and monitored according to vegetation cover and its variations in time and space. This cover is, therefore, often used as an indicator in the remote sensing of land condition. Remote sensing has developed as a powerful tool in environmental studies (Oštir *et al*. 2003) because it can provide calibrated, objective, repeatable and cost effective information for large areas and it can be empirically related to field data collected by traditional means (Graetz 1987; Tueller 1987; Pickup 1989). One of the most common applications of remote sensing is vegetation monitoring and assessment via vegetation indices which combine reflectance measurements from the bands of sensing instruments (Pickup *et al*. 1993; Bannari *et al*. 1995; Purevdorj *et al*. 1998; Thiam and Eastman 2001). However, most of the widely used vegetation indices are inappropriate in arid and semi-arid environments of Australia where perennial vegetation dominates. These plants often lack the contrast between red and infrared reflectance upon which the common vegetation spectral indices are based, making them difficult to distinguish from red-coloured soils. Several alternative multispectral indices that place less emphasis on vegetation infrared response are more appropriate and have been widely used in Australian arid and semi-arid rangelands (Foran and Pickup 1984; Pickup and Nelson 1984; Pickup and Foran 1987; Pickup *et al*. 1993; McGregor and Lewis 1996; O'Neill 1996).

Grazing lands held under pastoral leases cover 85% of the state of South Australia. The administration of these lands is governed by the South Australian Pastoral Land Management and Conservation Act, 1989, which aims to ensure sustainable utilisation and resource maintenance and which also provides for effective monitoring of the condition of the lands. Assessment and monitoring the condition of the pastoral lands has been undertaken by the Pastoral Management Branch of the Department of Water, Land Biodiversity and Conservation, under the direction of the Pastoral Board. In the southern sheep-grazing lands two methods are used for monitoring and assessing land condition; a land condition index and permanent monitoring sites, both field-based methods (Department of Water, Land Biodiversity and Conservation 2002). For the land condition index, land condition is determined through comparison with descriptions and photo standards at numerous randomly located sites on each lease. In addition, permanent monitoring sites have been established in most paddocks to determine temporal trends in land condition. Sampling at some of these sites is repeated at infrequent intervals and comprises assessment of plant density and cover, together with repeated photography from a photopoint (Department of Water, Land Biodiversity and Conservation 2002).

Although these ground-based methods provide detailed data about specific sites at infrequent monitoring intervals, they

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represent a very limited sample of the full extent and spatial variation within much broader areas of rangelands. Furthermore, such field assessment is time-consuming, expensive and subject to observer variation (Friedel and Shaw 1987*a*, 1987*b*). Consequently, the aim of this study was to evaluate the suitability of vegetation indices derived from satellite imagery as an adjunct to field methods for assessing and monitoring vegetation cover, and consequently land condition, in the southern rangelands of South Australia. Specifically, we aimed to identify the most suitable image indices for recording vegetation cover in these landscapes, to determine the scales at which they may be applied, and the components of vegetation cover that they best predict. Our approach was to determine the relationships between a range of widely used spectral indices and vegetation cover as measured by the South Australian Pastoral Lease Assessment Program, with the intention to produce image maps that more fully document spatial and temporal variation in vegetation cover.

Vegetation indices

Vegetation indices combine reflectance measurements from different portions of the electromagnetic spectrum to provide information about vegetation cover on the ground (Campbell 1996). Healthy green vegetation has distinctive reflectance in the visible and near-infrared regions of the spectrum. At visible, and in particular, red wavelengths, plant pigments strongly absorb the energy for photosynthesis, whereas in the near-infrared region, the energy is strongly reflected by the internal leaf structures. This strong contrast between red and near-infrared reflectance has formed the basis of many different vegetation indices. When applied to multispectral remote sensing images, these indices involve numeric combinations of the sensor bands that record land surface reflectance at various wavelengths.

Pearson and Miller (1972) first presented the near infrared/red ratio for separating green vegetation from soil background. Since then, numerous vegetation indices have been proposed, modified, analysed, compared and classified (Huete 1988; Qi *et al*. 1994; Bannari *et al*. 1995). For our evaluation we have grouped vegetation indices into four types on the basis of the spectral bands they use and the means by which these are combined. Definitions of the indices are provided in Table 1.

The first group, slope-based vegetation indices, are simple arithmetic combinations of reflectance measurements,

Table 1. Vegetation indices compared in this study

Vegetation index group	Vegetation index	Acronym	Author	Formula	Landsat TM bands
Group 1 (Slope-based)	Simple	SVI	Pearson and Miller (1972)	NIR/R	4/3
	Normalised difference	NDVI	Rouse *et al*. (1974)	(NIR − R)/(NIR + R)	(4 − 3)/(4 + 3)
	Soil adjusted-A	SAVI-A	Huete (1988)	[(NIR − R)/(NIR + R + L)] × (L + 1), where L is soil adjusted factor	[(4 − 3)/(4 + 3 + 0.25)] × 1.25
Group 2 (Distance-based)	Perpendicular vegetation index-3	PVI-3	Qi *et al*. (1994)	A × NIR − B × R, where A is the intercept of soil line and B is the slope of soil line	A × 4 − B × 3
	Perpendicular distance	PD54	Pickup *et al*. (1993)	Perpendicular distance from soil line towards vegetation line	2 *v*. 3
	Soil stability index	SSI	Pickup and Nelson (1984)	Perpendicular distance from soil line towards vegetation line	2/4 *v*. 3/4
Group 3 (Orthogonal transformations)	Soil brightness index	SBI	Kauth and Thomas (1976)	Orthogonal transformation	All bands except band 6
	Green vegetation index	GVI	Kauth and Thomas (1976)	Orthogonal transformation	All bands except band 6
Group 4 (Plant–water sensitive)	Stress related-1	STVI-1	Thenkabail *et al*. (1994)	(MIR × R)/NIR	(5 × 3)/4
	Stress related-3	STVI-3	Thenkabail *et al*. (1994)	NIR/(R + MIR)	4/(3 + 5)
	Mid-infrared-1	MSVI-1	Thenkabail *et al*. (1994)	NIR/MIR	4/5
	Mid-infrared-2	MSVI-2	Thenkabail *et al*. (1994)	NIR/SWIR	4/7
	Mid-infrared-3	MSVI-3	Thenkabail *et al*. (1994)	NIR/(MIR + SWIR)	4/(5 + 7)

contrasting the high infrared and low red reflectance that characterises photosynthetic vegetation. This contrast has been widely used to generate several vegetation indices such as the simple vegetation index (SVI) (Pearson and Miller 1972), normalised difference vegetation index (NDVI) (Rouse *et al*. 1974), and soil adjusted vegetation index (SAVI-A) (Huete 1988). The NDVI has been widely used in many applications including regional and continental-scale monitoring of vegetation cover (Satterwhite and Henley 1987; Foran and Pearce 1990; Myneni *et al*. 1997; Wang *et al*. 2004; Wessels *et al*. 2004).

The second group consists of distance-based vegetation indices. These indices have been designed to remove the influence of soil brightness in sparsely vegetated areas; they are more effective at discriminating vegetation from bright soils when the two are mixed within the sensor field of view. These indices take advantage of the fact that most soil-dominated pixels fall along a line in a red/near-infrared bi-spectral plot, with vegetation increasing with distance perpendicular to this line. The soil line can influenced by surface roughness, moisture, texture and colour (Huete *et al*. 1984; Baret *et al*. 1993). The perpendicular vegetation index (PVI) (Richardson and Wiegand 1977) was the first of this type of index. The PD54, which has been used with considerable success in Australian perennial-dominated arid vegetation, also falls within this group (Pickup *et al*. 1993).

The slope-based and distance-based vegetation indices generally use two spectral bands, most usually red and infrared. Orthogonal transformation vegetation indices, the third group, use multiple spectral bands to derive a new set of image components that are uncorrelated with one another and ordered with respect to the amount of scene variation they capture from the original band set (Kauth and Thomas 1976; Fung and LeDrew 1987). The first component usually represents brightness, often related to soil exposure, and the second component often represents variation in green vegetation cover. This group has been used in numerous environmental studies for vegetation mapping and monitoring land cover changes (Byrne *et al*. 1980; Ingebritsen and Lyon 1985; Dymond *et al*. 2002; Price *et al*. 2002; Jin and Sader 2005). The tasselled cap transformation is the best-known of this group (Kauth and Thomas 1976): its two first components are the soil brightness index (SBI) and the green vegetation index (GVI). This transformation was adapted to the six bands of Landsat thematic mapper (TM) data by changing the empirical coefficients from those originally applied to the four bands of Landsat multispectral scanner imagery (Crist 1985).

In addition to the soil brightness that is considered in the second and third group of indices, soil colour can also influence vegetation indices. Red and yellow soils with high red reflectance can particularly interfere with vegetation estimation. To address this problem, a colouration index, the redness index (RI), has been presented as a correction for the soil colour effect on vegetation indices (Bannari *et al*. 1995). The index, based on the contrast between red and green reflectance, was shown to double the sensitivity of vegetation indices, especially in sparsely vegetated areas.

The fourth group consists of vegetation indices that include mid and short-wave infrared regions of the electromagnetic spectrum, on the basis that vegetation has lower reflectance than soil in these regions, a contrast that may assist their discrimination (Kimes *et al*. 1981; Dusek *et al*. 1985; Baret *et al*. 1988; Thenkabail *et al*. 1994). Since it is water content that largely determines plant reflectance in the near infrared, mid and shortwave infrared regions, these have been called plant–water sensitive vegetation indices. Thenkabail *et al*. (1994) proposed six different plant–water sensitive vegetation indices using Landsat TM mid-infrared and shortwave-infrared bands, including the mid-infrared vegetation index (MSVI 1, 2 and 3) and the stress related vegetation index (STVI-1, 2 and 3). They found that these indices were as good or better predictors of yield, leaf area index, wet biomass, dry biomass, and plant height than slope-based vegetation indices in corn and soybean fields. O'Neill (1996) applied these indices to chenopod shrublands in western New South Wales and suggested that STVI-1 can be a useful index for vegetation mapping and analysis in these environments.

Most of the widely used vegetation indices that use red and NIR regions of the spectrum appear to be inappropriate in Australian arid and semi-arid lands (O'Neill 1996) because the perennial vegetation types of these regions do not reflect highly in the NIR (Graetz and Gentle 1982). Moreover, the sparse cover and low leaf area index of the vegetation also contribute to low reflectance in the NIR channel. To address this problem Pickup *et al*. (1993) developed the perpendicular distance vegetation index (PD54). This index falls within Group 2, but uses visible green and red reflectance to separate vegetation cover from soil (Bastin *et al*. 1999). Pickup *et al*. (1993) found that this index is less sensitive than red and NIR indices to differences in plant greenness. The PD54 has been widely evaluated for rangeland monitoring and assessment in Australia (Bastin *et al*. 1993*a*, 1993*b*, 1998; Pickup *et al*. 1994; McGregor and Lewis 1996). The soil stability index (SSI) is another distance-based vegetation index developed to assess soil condition in Australian arid rangelands (Pickup and Nelson 1984). Although the SSI provided useful information about soil erosion, stability, and deposition, it appeared to be more sensitive than PD54 to the amount of vigorous green vegetation in the landscape, responding to both perennial and ephemeral cover.

Materials and methods

Study area

The study area was located in the Kingoonya Soil Conservation District (KSCD) in the southern rangelands of South Australia (Fig. 1). The region lies within latitudes 29°30′ and 31°30′S and within longitudes 133°00′ and 136°00′E, covering an area of 65 815 km^2. The climate in this area includes hot summers and cold–mild winters. Rainfall is highly variable from year-to-year, with average annual totals ranging from less than 150 mm in the north-east to around 200 mm in the south-west (Kingoonya Soil Conservation Board 1996). The main land types of the district are sand plains with open woodland, calcareous plains with pearl bluebush (*Maireana sedifolia* F.Muell.) and bladder saltbush (*Atriplex vesicaria* Benth.), sand dunes with native pine (*Callitris glaucophylla* Joy Thoms and L.A.S.Johnson) or mulga (*Acacia aneura* F.Muell. ex Benth.), tableland with bladder saltbush and samphire (*Halosarcia pergranulata*

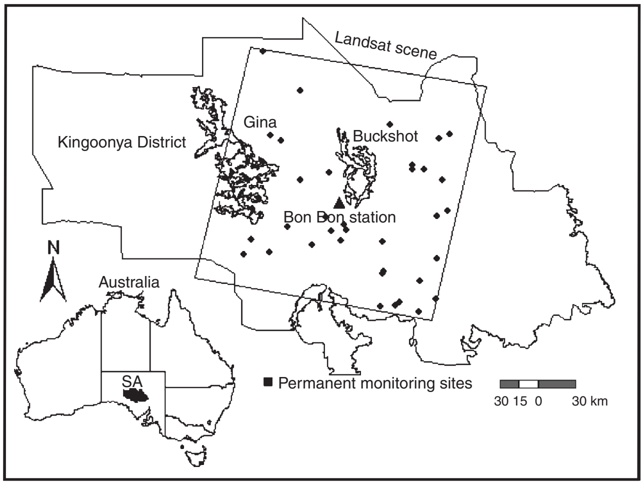

Fig. 1. Location of study area within the Kingoonya Soil Conservation District. Shown also are Buckshot and Gina land systems which were used for land-system scale analysis.

J.M.Black), gravel plains with mulga and dead finish (*Acacia tetragonophylla* F.Muell. Kurara), alluvial plains with low shrublands of pearl bluebush and bladder saltbush, low hills with low bluebush (*Maireana astrotricha* L.A.S.Johnson) and mulga and granitic hills. The pastoral stations are primarily managed for sheep grazing for wool and meat production (White and Gould 2002).

We analysed the relationships between vegetation cover and satellite image indices at two scales: across 34 225 km^2 covered by a Landsat scene, which encompassed ten different land systems, and within two particular land systems: Buckshot and Gina. Buckshot land system (498 km^2) comprises 'buckshot' gravel (iron-oxide coated gravels) plains and watercourses of mulga low woodland, and Gina land system (1601 km^2) is dominated by sandy calcareous plains of pearl bluebush (Table 2).

Field data

The Kingoonya Soil Conservation District was one of the first districts to be assessed after enactment of the South Australian Pastoral Land Management and Conservation Act in 1989. Over 1000 permanent monitoring sites were established throughout the district as part of the land condition assessment program conducted by the Pastoral Management Branch. The sites were generally located ~1.5 km from permanent water points, in areas considered to be representative of their surroundings. At this distance from water, the sites experience considerable grazing, but are not as severely degraded as areas closer to permanent water points.

Table 2. Characteristics of Buckshot and Gina land systems (Pastoral Board 1991)

Land system	Description
Buckshot	Mt Eba buckshot gravel plains. Plains of mulga low open woodland with dead finish, emubush and low bluebush; gilgai plains of cottonbush with Mitchell grass, neverfail, some saltbush and bluebush; mulga woodland watercourses with dead finish and emubushes.
Gina	Extensive sandy calcareous plains. Calcareous plains of pearl bluebush low shrubland with hopbush and cassia; sand spreads of mulga open woodland over cassia and grasses; run-on flats of mulga and dead finish over grasses.

The vegetation cover data used in this study were collected at permanent monitoring sites as part of lease assessments in 1990–91: sites within Gina and Buckshot were recorded in October 1990 and April 1991, while sites across the district were recorded in October and December 1990 and between March and June 1991. Rainfall in the study area was below average during these years (140 and 102 mm recorded at Bon Bon station in 1990 and 1991). Monthly rainfall during and immediately preceding the data collection periods was generally low, with some localised falls during January and May 1990 (Fig. 2).

The field data comprised estimates of ground cover derived from step point transects with a minimum of 500 points or hits (Department of Water, Land Biodiversity and Conservation 2002). Linear transects originated from the permanent monitoring sites, although the specific direction was not recorded. For this study we aggregated the cover data into three groups to compare with image indices: perennial plant cover, combined perennial and ephemeral plant cover, and total vegetation plus litter and soil-covering cryptogam cover. Owing to their longevity and lower sensitivity to seasonal conditions, perennial plants are usually used as a key indicator of land condition. As a result, strong relationships between perennial cover and vegetation indices means that image indices have a capability for land condition assessment and monitoring. Forty monitoring sites from across the district representing ten different land systems with varying land form, vegetation and soils were used to evaluate relationships of perennial plants and other cover components with image indices at landscape scale (Fig. 1), while eight and 19 sites were used to test relationships in Buckshot and Gina land systems. These two land systems were chosen for analysis because they are extensive, they have contrasting landscapes, and because they contained sufficient monitoring points to allow statistical comparisons of field and image variables.

Total vegetation cover averages were similar for the two land systems, at 20 and 21% in Gina and Buckshot respectively, compared with a mean of 19% for all sites (Table 3). Buckshot had higher ephemeral and grass cover (13%) and lower perennial cover (8%) than Gina and the regional average (12%). Litter and cryptogam cover were significant contributors to total ground cover at 23 and 30% for Buckshot and Gina, and 27% for all sites, bringing total ground cover to 45–50%.

Satellite data

A full scene of Landsat thematic mapper (TM) imagery from 20 October 1991 (path 100, row 81) was acquired and geometrically rectified to Map Grid of Australia (MGA) coordinates. Because field data collection spanned several months in 1990–91 it was not possible to acquire an image that coincided with all field data dates. However, the imagery

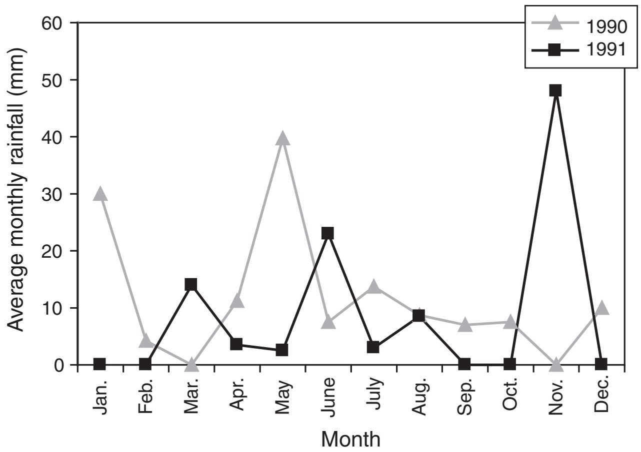

Fig. 2. Monthly average rainfall of 1990 and 1991 recorded at Bon Bon station within the study area (Pastoral Board 1991).

captured similar dry conditions, with only 10 mm of rain falling during the preceding 4 months. The dry summer image minimised the contribution of green ephemeral vegetation, maximised solar irradiance and land surface reflectance and also excluded cloud cover from the scene.

The vegetation indices detailed in Table 1 were calculated using the Landsat image bands. In addition to these indices, we devised a new stress related vegetation index (STVI-4). This index is a variant of the plant-water sensitive group, and was designed to respond positively to increasing vegetation response, whereas the existing STVI indices decrease with increasing vegetation influence. It was calculated using Landsat red band 3 (0.63–0.69 µm), near-infrared (NIR) band 4 (0.76–0.90 µm) and mid-infrared (MIR) band 5 (1.55–1.75 µm) with the following formula:

$$\text{STVI-4} = \text{NIR} - (\text{RED} \times \text{MIR})/(\text{NIR} + \text{MIR})$$

The index contrasts the higher NIR reflectance of vegetation with chlorophyll absorption in the red and water absorption in the MIR. Because of xeromorphic adaptations and low chlorophyll levels the visible red reflectance of arid plants may be high, but the MIR reflectance may be low in response to moisture content, particularly of semi-succulent chenopods. Therefore, in this study, the [NIR − (RED × MIR)] operation instead of (NIR − RED) that was used in the NDVI formula was used to highlight vegetation cover. By normalising the [NIR − (RED × MIR)] operation over (NIR + MIR) instead of (NIR + RED) as in the NDVI formula, the effects of soil background were significantly reduced and highlighted the sparse vegetation cover in this arid environment. This normalisation retains the ability of the index to minimise topographic and atmospheric effects.

This index was also corrected using the redness index (Bannari *et al*. 1995). This index calculates the difference between red and green reflectance, normalised by their sum, defined by the following equation:

$$\text{redness index} = (\text{R} - \text{G})/(\text{R} + \text{G})$$

where R is the mean reflectance in the red channel, and G is the mean reflectance in the green channel.

The method uses the slope ‘K’ obtained from the correlation between RI and the vegetation index, in this case the STVI-4. This produced a corrected vegetation index, VI*:

$$\text{VI}^* = \text{STVI-4} - \text{KRI}$$

Each of the permanent monitoring sites was located on the rectified satellite image and average pixel values extracted for each of the vegetation indices within a 150 m radius from the point. Field data were collected from transects up to 750 m from the monitoring sites, although the direction of these was not recorded. Consequently there was some uncertainty about the precise image location and area that coincided with the field transects. To address this, we extracted mean values from buffers of 100, 150, 300, and 400 m. around the monitoring points, and evaluated the comparative strength of relationships between the image and field data. This preliminary assessment showed that the 150 m radius buffer yielded the strongest relationships with the field data.

Data analyses

The relationships between field cover data, aggregated into different categories, and vegetation indices were tested with simple linear regression. To investigate the influence of spectral variations on the vegetation indices, relationships between field cover data and vegetation indices were tested at two different scales: landscape scale, using the 40 monitoring sites across the whole Landsat scene, and land system scale with less spectral variation, using the eight and 19 samples in Buckshot and Gina.

Results

The regression relationships between field cover data and vegetation indices at landscape scale, across the Landsat scene,

Table 3. Vegetation cover components at landscape and land system scales
Values are means (s.d.)

Vegetation components	Cover (%)		
	Study area ($n = 40$)	Buckshot land system ($n = 8$)	Gina land system ($n = 19$)
Perennial species	12.1 (7.4)	7.9 (6.2)	12.4 (6.5)
Ephemeral and grass species	6.8 (5.3)	13.5 (12.3)	8 (5.4)
Total vegetation (perennial, ephemeral and grass species)	18.9 (8.7)	21.4 (16.3)	20.4 (8.1)
Litter and cryptogams	27 (14.5)	22.7 (9.3)	29.5 (10.1)
Total vegetation plus litter and cryptogams	45.9 (16.6)	44.1 (19.3)	49.9 (9.9)

are given in Table 4. At this scale, an area that includes 10 different land systems, all the slope-based vegetation indices were significantly correlated with field cover data, with the strongest relationships with combined plant, litter and cryptogam cover explaining up to 35% of the variation in field measurements. The PVI-3 and PD54 of the distance-based vegetation indices were also significantly correlated with total vegetation and total organic cover, explaining 18–20% of cover variation, but their relationships with perennial plant cover were not significant. Similar results were obtained with the orthogonal vegetation indices (SBI and GVI). The SBI, a weighted sum of the Landsat image bands, equating to total ground reflectance or albedo was negatively correlated with total ground cover, while the GVI showed a stronger positive relationship. The PVI-3 and PD54 predicted total vegetation cover and total organic ground cover, but the SSI from the same group of distance-based vegetation indices was not significantly related to any of the field cover components. The plant–water sensitive vegetation indices (Group 4) showed variable relationships with field data. Among these indices, the stress related vegetation indices (STVI-1 and 4) were significantly correlated ($R^2 = 0.1$–0.3) with all combinations of field cover components, although they explained relatively low proportions of the variance in the field measurements. Other vegetation indices in this group were less consistent predictors of field cover.

Within the two land systems, as we expected, there were stronger relationships between vegetation indices and field cover data than at the broader scale. Table 5 shows these relationships in the Buckshot land system. The STVI-1 showed the strongest relationship with total vegetation cover ($R^2 = 0.88$), followed by the SBI ($R^2 = 0.82$) and STVI-4 ($R^2 = 0.78$). There were significant correlations between the slope-based indices and total vegetation cover ($R^2 = 0.6$) but these indices were very poor predictors of perennial vegetation cover or total organic cover. In contrast to the regional analysis, all the distance-based and orthogonal transformation indices were significantly correlated with all categories of field cover data in this land system, although the strongest relationships were with total vegetation cover. However, the STVI-3 and MSVI versions 1, 2 and 3 showed no significant correlations with field cover data.

In the Gina land system all the relationships were significant at the 95% confidence level with the exception of the slope-based indices that were poorly related to total ground cover (Table 6). The vegetation indices generally best predicted total plant cover, followed by perennial plant cover. The strongest relationships were between GVI and total vegetation cover ($R^2 = 0.74$) followed by STVI-4 ($R^2 = 0.66$).

Discussion

The prediction of vegetation cover was stronger within the two land systems studied than across the range of land systems within the region. Across the study area up to 40% of the variation in cover was explained, whereas within land systems the vegetation indices explained up to 90% of variation in cover measurements. The stronger predictive power of the vegetation indices within land systems is not unexpected, as soils and vegetation are usually more homogeneous and resultant spectral variations are lower at this scale. At regional or landscape scale the relationships between cover and spectral response are more varied, and although they may be strong within land systems, are weaker when the land systems are aggregated together.

Across the region the vegetation indices best predicted total cover comprising the combination of perennial and ephemeral plants with surface plant litter and cryptogam crust, followed by the less abundant total plant cover and perennial plant cover, suggesting that it is the reduction in overall landscape reflectance brought about by the organic cover that is influencing the spectral indices. In contrast, the cover components best predicted within the two land systems were total plant cover and perennial plant cover, with the combined cover components poorly predicted. The strength of the cover prediction is noteworthy, since the total plant cover was only 20–21% and the perennial cover

Table 4. Relationships between field cover and vegetation indices at landscape scale across the whole Landsat scene
Values are R^2 (*P*)

Vegetation index group	Vegetation index	Cover (%) Perennial plants	Total vegetation	Total vegetation, litter and cryptogams
Group 1	SVI	0.22 (0.002)	0.26 (0.001)	0.37 (0.001)
(Slope-based)	NDVI	0.22 (0.002)	0.2 (0.001)	0.39 (0.001)
	SAVI-A	0.22 (0.002)	0.26 (0.001)	0.38 (0.001)
Group 2	PVI-3	0.04 (0.208)	0.14 (0.019)	0.20 (0.003)
(Distance-based)	PD54	0.06 (0.117)	0.15 (0.015)	0.18 (0.006)
	SSI	−0.02 (0.333)	−0.01 (0.387)	−0.01 (0.774)
Group 3	SBI	−0.09 (0.061)	−0.19 (0.005)	−0.22 (0.002)
(Orthogonal transformation)	GVI	0.08 (0.069)	0.20 (0.003)	0.30 (0.001)
Group 4	STVI-1	−0.17 (0.009)	−0.26 (0.001)	−0.23 (0.002)
(Plant–water	STVI-3	0.28 (0.001)	0.12 (0.029)	0.01 (0.917)
sensitive)	STVI-4	0.10 (0.048)	0.21 (0.003)	0.26 (0.001)
	MSVI-1	0.10 (0.045)	0.01 (0.561)	−0.09 (0.063)
	MSVI-2	0.04 (0.225)	−0.01 (0.490)	−0.24 (0.001)
	MSVI-3	0.07 (0.091)	−0.01 (0.964)	−0.17 (0.009)

Table 5. Relationships between field cover data and vegetation indices in Buckshot land system
Values are R^2 (P)

Vegetation index group	Vegetation index	Cover (%) Perennial plants	Total vegetation	Total vegetation, litter and cryptogams
Group 1	SVI	0.02 (0.325)	0.57 (0.030)	0.24 (0.215)
(Slope-based)	NDVI	0.03 (0.314)	0.58 (0.020)	0.26 (0.196)
	SAVI-A	0.01 (0.329)	0.57 (0.031)	0.24 (0.217)
Group 2	PVI-3	0.71 (0.008)	0.78 (0.003)	0.61 (0.022)
(Distance-based)	PD54	0.61 (0.013)	0.72 (0.008)	0.62 (0.021)
	SSI	−0.44 (0.044)	−0.61 (0.022)	−0.62 (0.020)
Group 3	SBI	−0.71 (0.008)	−0.82 (0.001)	−0.63 (0.018)
(Orthogonal transformation)	GVI	0.68 (0.012)	0.64 (0.017)	0.55 (0.036)
Group 4	STVI-1	−0.64 (0.011)	−0.88 (0.001)	−0.65 (0.015)
(Plant–water	STVI-3	−0.07 (0.260)	−0.08 (0.500)	−0.12 (0.404)
sensitive)	STVI-4	0.71 (0.008)	0.78 (0.003)	0.62 (0.019)
	MSVI-1	−0.01 (0.437)	−0.01 (0.914)	−0.04 (0.633)
	MSVI-2	−0.39 (0.057)	−0.20 (0.267)	−0.20 (0.264)
	MSVI-3	−0.16 (0.178)	−0.06 (0.554)	−0.11 (0.421)

Table 6. Relationships between field cover data and vegetation indices in Gina land system
Values are R^2 (P)

Vegetation index group	Vegetation Index	Cover (%) Perennial plants	Total vegetation	Total vegetation, litter and cryptogams
Group 1	SVI	0.37 (0.005)	0.65 (0.001)	0.12 (0.146)
(Slope-based)	NDVI	0.36 (0.006)	0.64 (0.001)	0.10 (0.168)
	SAVI-A	0.36 (0.006)	0.64 (0.001)	0.12 (0.145)
Group 2	PVI-3	0.49 (0.001)	0.61 (0.001)	0.47 (0.001)
(Distance-based)	PD54	0.40 (0.003)	0.54 (0.001)	0.54 (0.001)
	SSI	−0.32 (0.013)	−0.22 (0.040)	−0.60 (0.001)
Group 3	SBI	−0.53 (0.001)	−0.64 (0.001)	−0.32 (0.004)
(Orthogonal transformation)	GVI	0.60 (0.001)	0.74 (0.001)	0.33 (0.010)
Group 4	STVI-1	−0.49 (0.001)	−0.60 (0.001)	−0.29 (0.018)
(Plant–water	STVI-3	−0.21 (0.045)	−0.22 (0.004)	−0.54 (0.001)
sensitive)	STVI-4	0.51 (0.001)	0.66 (0.001)	0.41 (0.001)
	MSVI-1	−0.32 (0.011)	−0.46 (0.001)	−0.53 (0.001)
	MSVI-2	−0.24 (0.035)	−0.49 (0.001)	−0.37 (0.006)
	MSVI-3	−0.30 (0.015)	−0.52 (0.001)	−0.48 (0.001)

8% and 12% in Buckshot and Gina. The poorer relationships between the spectral indices and total cover (plants, litter and cryptogams) within the land systems suggest that the indices are indeed responding to the reflectance characteristics of photosynthetic vegetation, rather than the simple ‘darkening’ effect of cover on the soil.

Across the land systems the best vegetation indices were the slope-based group, which explained up to 40% of total cover variation, followed by some of the stress-related indices and the green vegetation index (20–30% of cover variation). There was little difference between the performance of NDVI, the simple red/infrared ratio vegetation index (SVI) and the soil-adjusted vegetation index (SAVI-A) in predicting total cover at this scale. The distance-based indices performed less well at this scale, explaining only around 20% of total cover variation. These poor correlations result from the dependency of these indices on specific landscape spectral characteristics in the image. All distance-based vegetation indices rely on the definition of a soil line, with vegetation cover estimated by the perpendicular distance from it in bi-spectral space. This soil line depends on soil type and colour and varies between different land systems. Thus, it would be poorly defined for the whole scene, which included 10 different land systems. In addition, these indices (e.g. PD54) require definition of a point of maximum vegetation cover in bi-spectral space, also a feature that is likely to vary across different land systems.

Within Gina and Buckshot, many of the vegetation indices were strongly correlated with total plant cover, explaining 60–90% of the variation in the monitoring point measurements. Strong relationships were recorded for both land systems, despite their marked differences in soil type and colour and dominant vegetation species. The best image indices were from the orthogonal and stress-related (STVI) group, followed by the distance-based and slope-based indices. Predictions of total plant cover were somewhat stronger in the Buckshot land system, even though it had lower perennial plant cover (8 *v.* 12%), and the soils are covered by iron-oxide coated 'buckshot' gravels which considerably add to the visible red reflectance and may interfere with vegetation discrimination.

Of the orthogonal indices, both the soil brightness index and the green vegetation index were strongly correlated with all cover components, the soil brightness index showing negative relationships with plant cover, as expected, because it is a weighted sum of the satellite image bands, recording brightness that is usually related to exposed soils. The orthogonal indices were somewhat poorer predictors of combined vegetation, litter and cryptogam cover, compared with vegetation cover alone. This may be because the spectral responses of dry plant litter and dark cryptogam crust are more likely to be found in the third component of the tasselled cap transformation rather than the first and second ones.

Responses of the stress-related indices were variable. The mid-infrared indices (MSVI 1, 2, and 3) were significantly correlated with all cover components in Gina, but were very poor predictors in Buckshot. Examination of the vegetation index images suggested that these indices were highly influenced by the variations in the soil background in this arid environment. However, the stress related indices, in particular STVI-1 and 4, were good predictors of cover in both land systems. The STVI-4, here applied with the soil colour correction, showed little improvement over existing indices of this type (STVI-1) in Buckshot, but performed better in Gina. Although the STVI-4 did not perform statistically significantly better than STVI-1, it had positive relationships with vegetation cover and this made STVI-4 imagery easier to interpret than STVI-1. In addition, cover mapping using the red-corrected STVI-4 showed better discrimination of vegetation patterns.

The distance-based indices were good predictors of total vegetation cover, and to a lesser degree of perennial vegetation cover within the two land systems. Within a land system soil types are more consistent and better represented by a single soil line in a bi-spectral space. As a result, distance from the soil line was a better indicator of vegetation cover. Several of distance-based vegetation indices (e.g. PD54) have been used successfully as indicators of perennial plant cover which has an important role in land condition assessment and monitoring in shrub-dominated arid-land systems, irrespective of plant greenness, and correlations here confirm their utility within land systems, but not across broader landscapes.

In considering predictive relationships between image spectral indices and the field cover measurements at the monitoring points, it must be remembered that the cover data were collected over several months, and that the imagery has captured landscape conditions at one time during this period. The Gina and Buckshot field data were collected in two months, although they were six months apart, while the monitoring points across the whole region were measured over a 9-month period. Consequently temporal variation in vegetation cover and its photosynthetic status, resulting from continuing grazing and from responses to changing weather and rain, must be considered as contributors to variability in the field data. In addition, slight mismatch between the precise area sampled in the field and the pixels extracted from the imagery could also potentially reduce the strength of relationships between the two datasets. The field cover data were collected from transects radiating up to 750 m from the monitoring points, while the image values came from areas of 7 ha around the points in order to include corresponding location. Finally, the field measurements were made by several different field workers, adding another source of variation to the data. For example, it has been shown that there may be up to 20% difference in measurements of plant cover made by experienced field workers, using objective methods similar to those made at the pastoral lease monitoring sites (Friedel and Shaw 1987*b*; Wilson *et al.*1987).

Conclusions

Our findings have several implications for the use of multispectral vegetation indices in vegetation cover assessment and monitoring in this environment. First, it is clear that predictive relationships can be established between image-derived indices and vegetation cover assessed by familiar field techniques. Although total organic ground cover and total plant cover can be quantified by some image indices, it is most significant that perennial plant cover can be predicted, since this is the vegetation that is most important in assessment of rangeland condition and monitoring of long-term trend. This means that image indices could be used to determine vegetation cover and document its distribution across broad landscapes, providing more information about spatial variation than is possible with current ground-based methods. Image-derived maps can show variations in plant cover within paddocks, properties and land systems, and can direct grazing and land management. Image-based assessment of vegetation cover also opens the way for more frequent monitoring of land condition. At present the vegetation cover at some of the permanent monitoring points is surveyed at infrequent intervals, while the overall property and district condition is assessed on a 14 year cycle, as required by the Pastoral Land Management and Conservation Act. More frequent assessment and monitoring using conventional field methods would be prohibitively expensive. However, image-based assessment could be performed more frequently and cheaply to track short and longer-term trends in land condition.

Second, prediction of vegetation cover from image indices is best approached on a land system basis, rather than across broader landscapes comprising a wider range of terrain, soils and vegetation. Comparisons of cover derived from image indices can be made within land systems, but should be approached with caution across land systems, since the relationships between plant cover and image indices vary with vegetation and soil types. Stratification into land systems should be undertaken if vegetation cover is to be quantified from image indices. For similar reasons, such stratification has been an integral part of the image-based grazing-gradient approach to pastoral land condition assessment that has been implemented in northern rangelands of South Australia and in Central Australia (Bastin *et al.* 1993*b*, 1998).

One of the main objectives of this study was to identify vegetation indices that were the best predictors of vegetation cover, and hence land condition, in the land systems of the Kingoonya Soil Conservation District. Criteria that make an image-based vegetation index suitable for regional monitoring are strong relationships with perennial cover in the vegetation types of the district, ability to predict this cover within land systems and across broader regional landscapes, and an objective means of computation to ensure consistent application across different images and dates.

Although simple red-infrared contrast indices, in particular NDVI, have been widely used with success in arid land studies throughout the world, our results confirm that they are not the best indices for recording perennial plant or total plant cover in several of the chenopod shrub-dominated land systems of southern Australia. However, we found they were the best predictors of combined plant, plant litter and cryptogam cover at a broad landscape scale that included a diversity of land systems across the 34 225 km^2 study region. This suggests that NDVI and simple red-infrared indices are useful for general cover monitoring regardless of more localised soil and vegetation variation.

Although distance-based indices, in particular the PD54, have been used with success in other Australian rangeland studies, they were not the strongest predictors of perennial or total plant cover in the land systems we studied, even though these were dominated by chenopods and other perennial shrubs, and had relatively low ephemeral plant cover. A further difficulty with distance-based vegetation indices that inhibits their use in broad-scale repeated monitoring programs is the need to subjectively define a soil line and vegetation dominated pixels in bi-spectral space. This process requires considerable expertise in image analysis, is subjective, and may lead to inconsistencies in application of the index.

Of the indices we evaluated, the stress related indices 1 and 4 (STVI-1, 4) performed best in relation to our criteria. They showed high to very high correlations with vegetation cover within land systems and significant relationships with cover at landscape scale. Generally, they best predicted combined perennial and ephemeral plant cover, as did O'Neill (1996) in a vegetation community dominated by chenopod shrublands in western New South Wales. However, they were also good predictors of perennial vegetation and of total ground cover. Their consistency of performance at different landscape scales suggests that these indices are less sensitive than others to variations in soil and vegetation within the Kingoonya District. An additional strength of these indices is that they are calculated using arithmetic combination of Landsat TM image bands, and hence do not require subjective interpretation of soil and vegetation spectral expressions. Consequently, they are well suited for operational programs of broad-scale land cover monitoring.

There have been recommendations for several decades for the use of remote sensing methods, usually via vegetation indices, in rangeland monitoring. However, despite compelling arguments, uptake of remote sensing by rangeland management agencies is not universal. Impediments to wider use of the techniques include lack of remote sensing specialists in monitoring and assessment agencies and lack of understanding among land holders about the information that can be derived from remote sensing. In addition, there can be uncertainty about the interpretation of image indices in relation to more conventional field data in particular environments. Our study has addressed this last question for selected environments in the southern Australian arid rangelands.

Our results provide a strong foundation for the use of vegetation indices as an adjunct to field methods for assessment of land condition in southern Australia. Stress-related vegetation indices that use multispectral image bands in the red, near-infrared and mid-infrared appear to be good predictors of vegetation cover as measured by traditional monitoring methods at both land system and landscape scales within the Kingoonya District. Image-based monitoring can provide more information about vegetation condition and variation in space and time, and is more cost-effective than field methods. Image maps can provide a means of extrapolating from the current network of monitoring point locations, and could potentially supplement field-based land condition assessments.

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