The Egyptian Journal of Remote Sensing and Space Sciences (2011) **14**, 49–56

National Authority for Remote Sensing and Space Sciences

The Egyptian Journal of Remote Sensing and Space Sciences

www.elsevier.com/locate/ejrs
www.sciencedirect.com

Comparison the accuracies of different spectral indices for estimation of vegetation cover fraction in sparse vegetated areas

Susan Barati [a,1], **Behzad Rayegani** [a,*], **Mehdi Saati** [b,2], **Alireza Sharifi** [c], **Masoud Nasri** [b]

[a] *Young Researchers Club, Ardestan Branch, Islamic Azad University, Esfahan, Iran*
[b] *Islamic Azad University, Ardestan Branch, Esfahan, Iran*
[c] *Surveying and Geomatics Engineering Department, University of Tehran, Tehran, Iran*

Received 2 April 2011; revised 2 June 2011; accepted 3 June 2011
Available online 14 July 2011

KEYWORDS

Vegetation cover fraction;
Remote sensing;
LISS III;
Vegetation indices

Abstract Quantitative estimation of canopy biophysical variables are very important in different studies such as meteorology, agriculture and ecology, so knowledge of the spatial and temporal distribution of these variables would be highly beneficial. Meanwhile, remote sensing is known as an important source of information to estimate fractional vegetation cover in large areas. Today spectral indices have been very popular in the remote sensing of vegetation features. But often reflections of soil and rocks are much more than reflections of sparse vegetation in these areas, that makes separation of plant signals difficult. So in this study measured fractional vegetation cover of a desert area were evaluated with 20 vegetation indices in five different categories as the most appropriate category, or indicator for desert vegetation to be identified. The five categories were

* Corresponding author. Mobile: +98 9133044086.
E-mail addresses: s_barati@na.iut.ac.ir (S. Barati), rayegani@ut.ac.ir (B. Rayegani), saati@iauard.ac.ir (M. Saati), alirezasharifi@live.com (A. Sharifi), m_nasri@iauard.ac.ir (M. Nasri).
[1] Tel.: +98 3116818657.
[2] Mobile: +98 9121990950.

Peer review under responsibility of National Authority for Remote Sensing and Space Sciences.
doi:10.1016/j.ejrs.2011.06.001

ELSEVIER Production and hosting by Elsevier

including: (1) conventional ratio and differential indices such as NDVI; (2) indices corrected and derived from the traditional indicators such as NDVIc and GNDVI; (3) soil reflectance adjusted indices such as SAVI; (4) triangle indices based on three discreet bands in their equation (Green, Red and NIR) like TVI; and (5) non-conventional ratio and differential indices such as CI. According to the results of this research, DVI index with 0.668 the coefficient of determination (R^2) showed the best fractional vegetation cover estimation. But according to the sparse vegetation in desert areas and the results of this research it seems none of these indicators alone can accurately estimate the percentage of vegetation cover, however, to do a proper estimation it is possible to enter data of these indices in a multivariate regression model. Using this method enabled us to increase the coefficient of determination of fractional vegetation cover estimation model up to 0.797.

1. Introduction

Vegetation cover has important affects on energy interchange near the surface and the percentage of vegetation cover is considered as a suitable criterion to identify land degradation and desertification in arid and semiarid regions and its measurements can be used to study these processes (Xiao and Moody, 2005). Also, quantitative estimation of canopy biophysical variables, especially the vegetation cover fraction, is very important in different studies such as meteorology, agriculture and ecology, so knowledge of the spatial and temporal distribution of these variables would be highly beneficial (Lawrence and Ripple, 1998; Houborg et al., 2007). Remote sensing is an important data source to estimate the vegetation cover fraction in wide areas (Xiao and Moody, 2005) and satellite based indices have been used in many researches to estimate vegetation cover (Gilabert et al., 2002; Kallel et al., 2007; Jiang et al., 2008). By using these indices, many vegetation parameters such as leaf area, biomass and physiological activities can be evaluated (Baret and Guyot, 1991; Verrelst et al., 2008). Spectral vegetation indices that are based on red and near infrared reflections have the high correlation with leaf area index and canopy cover (Broge and Leblanc, 2000). However, in sparse vegetated areas, the reflection of soil and sand are much higher than reflection of vegetation and so detection of vegetation cover reflection is difficult. Therefore, soil reflectance adjusted indices such as Soil Adjusted Vegetation Indices (SAVI), Optimized Soil Adjusted Vegetation Indices (OSAVI) and Modified Soil Adjusted Vegetation Indices (MSAVI) had been developed in the passed (Karnieli et al., 2001; Gilabert et al., 2002; Shupe and Marsh, 2004). In this research, by using 20 different vegetation cover indices that are comprised of variety of different indices such as simple difference indices (e.g. DVI), simple ratio indices (e.g. SR), normalized difference indices (e.g. NDVI), soil adjusted indices (e.g. SAVI) and triangular indices (e.g. MTVI) the vegetation cover fraction has been estimated and their accuracies have been compared.

2. The study area

The study area comprises of a region with 22,118 hectare that located at the center of Iran near the Esfahan city (Fig. 1). Based on Bagnouls and Gaussen climate classification system (Bagnouls and Gaussen, 1957), the local area has desert climate and according to Emberger climate classification system (Emberger, 1955), it has cold-dry climate. The area has the maximum monthly mean temperature 46 °C in July and minimum monthly mean temperature −13 °C in January and means annual temperature is 19 °C.

Bulk of the study area have formed of rangelands, and in some scattered areas as close to rivers and seasonal watercourse, the farms are located (Fig. 2). White wormwood (*Artemisia herba-alba*) is dominant species and in many parts of study area it is only existing species. In some places other species such as Sagebrush (*Artemisia aucheri*), Boiss (*Scariola orientalis*), Syrian Rue (*Peganum harmala*), *Pteropyrum aucheri*, salt cedar (*Tamarix* spp.), *Acanthophyllum*spp., Forssk (*Lounaea spinosa*) are also observed.

3. Satellite data

The image of IRS-LISSIII has been used in this research. The satellite image was georeferenced by using the 50 ground control points. The Root Mean Square Error (RMSe) of 0.248 pixels has been obtained.

4. Ground data

Ground measurement of vegetation cover fraction was started on June-3-2010. The sampling sites are square areas with 36 m length to cover the pixel size of the image data. The study area has been visited to determine all the vegetation types. White wormwood (*Artemisia herba-alba*) was dominant species in most of study area. The positions of sampling sites have been chosen such that they composed of all the vegetation types. Totally 40 sites have been sampled (Fig. 3). In order to measure the vegetation cover fraction, some parallel transects with six meter separation distance have been used (Fig. 4). In each transect, the positions that canopy has contact with transect has been recorded and also the length of the contacts have been measured. Then, the mean percent of the contacts length to the total length of transect has been considered as vegetation cover fraction of that sampling site. In each corresponding pixels, the values of green, red, near infrared and short wave infrared bands have been recorded.

5. Methodology

In this research, five different class of vegetation index have been studied: (1) conventional ratio and differential indices such as Simple Ratio Index (SR), NDVI, DVI and Infrared Percentage Vegetation Index (IPVI); (2) corrected and modified conventional indices such as Corrected Simple Ratio Index

Figure 1 Location of the study area in central of Iran.

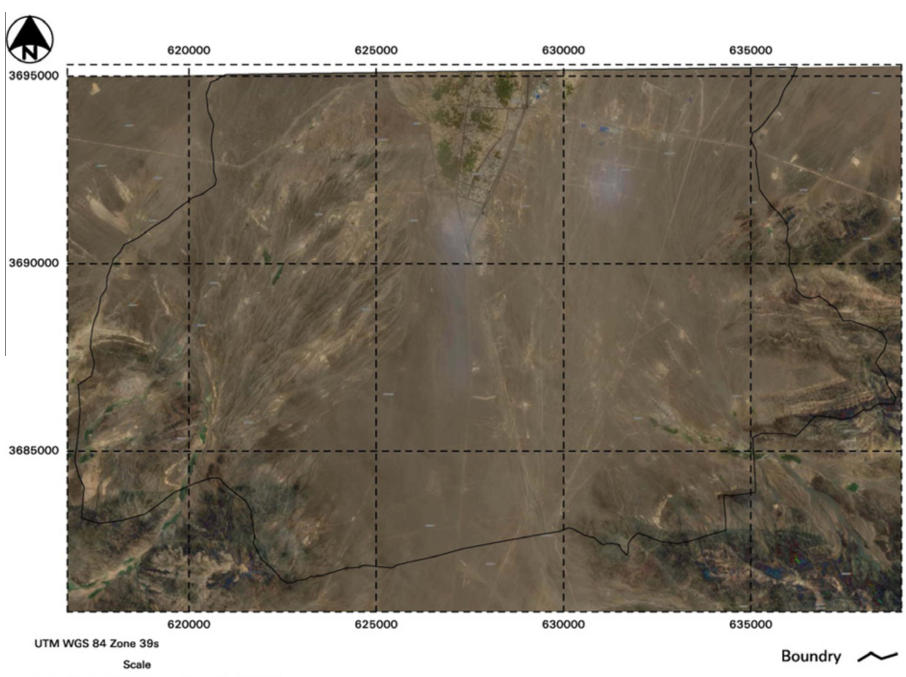

Figure 2 The satellite image of the study area.

(SRc), Modified Simple Ratio Index (MSR), NDVIc, GNDVI, Ratio Difference Vegetation Index (RDVI) and Non-Linear Index (NLI); (3) soil reflectance adjusted indices such as SAVI, Optimized Soil Adjusted Vegetation Index (OSAVI) and Modified Soil Adjusted Vegetation Index (MSAVI); (4) triangular indices that are based on green, red and infrared bands such as TVI, Modified Triangulation Vegetation Index-1 (MTVI1) and MTVI2; and (5) non-conventional ratio and differential indices such as Normalized Difference Infrared Index (NDII), Specific Leaf Area Vegetation Index (SLAVI), CI and Normalized Canopy Index (NCI). All these indices have been introduces in Table 1.

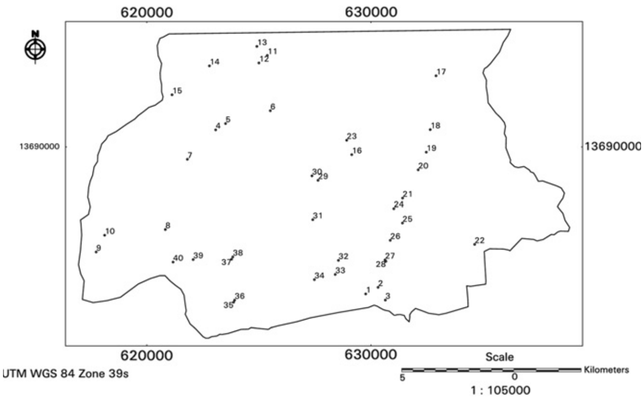

Figure 3 The locations of the sampling sites in the study area.

In Table 1, R_{SWIR}, R_{NIR}, R_{RED} and R_{GREEN} are spectral reflectance in shortwave infrared, near infrared, red and green bands, respectively. Also min and max are minimum and maximum reflectance or digital number on the corresponding spectral range. For all the 40 sampling sites, all the introduced indices and also their correlations with vegetation cover fraction have been estimated.

6. Results

The correlation between vegetation indices and vegetation cover fraction has been assessed for all the five vegetation classes.

6.1. Conventional ratio and differential indices

The results obtained from all the indices have been shown in Table 2. Regards to Table 2, the correlation between vegeta-

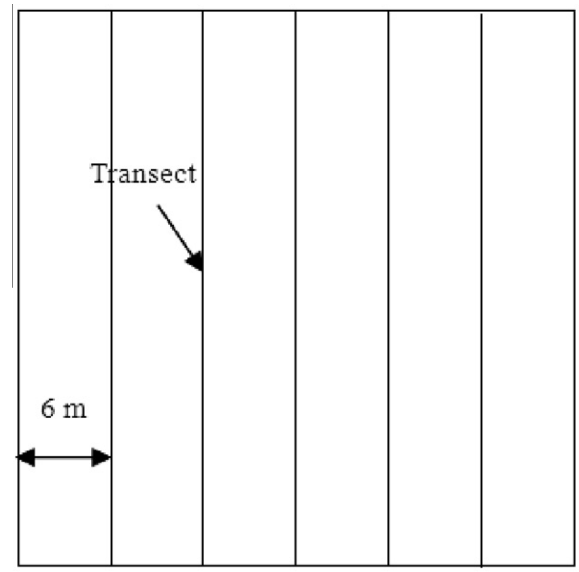

Figure 4 The sampling site and the transects.

tion cover and conventional ratio and difference indices are more than its correlation with other indices. Also DVI index has the highest correlation coefficient between all the indices. Absorption of electromagnetic waves in the red region by chlorophyll and its high reflectance in the near infrared region are the reasons of this high correlation coefficient in this class of indices (Tucker, 1980). Although NDVI has been used in many studies, but in high vegetation cover, this index is saturated and also its relation with biophysical vegetation is not linear (Haboudane et al., 2004; Vescovo and Gianelle, 2008; Jiang et al., 2008; Baret and Guyot, 1991; Gitelson, 2004). Due to

Table 1 The used indices.

Name	Equation	References
SR or RVI	$SR = \frac{R_{NIR}}{R_{RED}}$	Jordan (1969)
SRc	$SRc = SR(1 - ((R_{SWIR} - R_{SWIR\,min})/(R_{SWIR\,max} - R_{SWIR\,min}))$	Brown et al. (2000)
MSR	$MSR = (R_{NIR}/R_{RED} - 1)/((R_{NIR}/R_{RED})^{1/2} + 1)$	Chen (1996)
DVI	$DVI = R_{NIR} - R_{RED}$	Tucker (1980)
NDVI	$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}}$	Rouse et al. (1973)
NDVIc	$NDVIc = NDVI(1 - (R_{SWIR} - R_{SWIR\,min})/(R_{SWIR\,max} - R_{SWIR\,min}))$	Nemani et al. (1993)
GNDVI	$GNDVI = \frac{R_{NIR} - R_{Green}}{R_{NIR} + R_{Green}}$	Gitelson et al. (1996)
RDVI	$RDVI = \frac{R_{NIR} - R_{RED}}{\sqrt{R_{NIR} + R_{RED}}}$	Rougean and Breon (1995)
IPVI	$IPVI = \frac{R_{NIR}}{R_{RED} + R_{NIR}}$	Crippen (1990)
SAVI	$SAVI = \frac{(1+L)(R_{NIR} - R_{RED})}{(R_{NIR} + R_{RED} + L)}$	Huete (1988)
OSAVI	$OSAVI = \frac{(R_{NIR} - R_{RED})}{(R_{NIR} + R_{RED} + 0.16)}$	Rondeaux et al. (1996) and Steven (1998)
MSAVI	$MSAVI = 1/2[2R_{NIR} + 1 - \sqrt{(2R_{NIR} + 1) - 8(R_{NIR} - R_{RED})}]$	Qi et al. (1994)
NLI	$NLI = (R^2_{NIR} - R_{RED})/(R^2_{NIR} + R_{RED})$	Goel and Quin (1994)
TVI	$TVI = 0.5[120(R_{NIR} - R_{GREEN}) - 200(R_{RED} - R_{GREEN})]$	Broge and Leblanc (2000)
MTVI1 or MCARI1	$MTVI1 = 1.2[1.2(R_{NIR} - R_{GREEN}) - 2.5(R_{RED} - R_{GREEN})]$	Haboudane et al. (2004)
MTVI2 or MCARI2	$MTVI2 = \frac{1.5[1.2(R_{NIR} - R_{GREEN}) - 2.5(R_{RED} - R_{GREEN})]}{\sqrt{(2R_{NIR}+1)^2 - (6R_{NIR} - 5\sqrt{R_{RED}}) - 0.5}}$	Haboudane et al. (2004)
NDII or NDWI	$NDII = \frac{R_{NIR} - R_{SWIR}}{R_{NIR} + R_{SWIR}}$	Hardisky et al. (1983)
SLAVI	$SLAVI = R_{NIR}/(R_{RED} + R_{SWIR})$	Lymburner et al. (2000)
CI	$CI = R_{SWIR} - R_{GREEN}$	Vescovo and Gianelle (2008)
NCI	$NCI = \frac{R_{SWIR} - R_{GREEN}}{R_{SWIR} + R_{GREEN}}$	Vescovo and Gianelle (2008)

Table 2 Correlation coefficient between vegetation indices and vegetation cover fraction.

Vegetation index	SAVI	MSR	IPVI	RDVI	DVI	GNDVI	NDVIc	NDVI	SRc	SR
Correlation	0.720**	0.723**	0.719**	0.798**	0.817**	0.570**	0.674**	0.719**	0.765**	0.727**
Coefficient	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Significant level number	40	40	40	40	40	40	40	40	40	40
Vegetation index	NCI	CI	SLAVI	NDII	MTVI2	MTVI1	TVI	NLI	MSAVI	OSAVI
Correlation	0.195	0.170	0.699**	0.503**	0.555**	0.426**	0.588**	0.345*	0.710**	0.719**
Coefficient	0.229	0.295	0.000	0.001	0.000	0.006	0.000	0.029	0.000	0.000
Significant level number	40	40	40	40	40	40	40	40	40	40

Note: The significance level of 0.000 indicates that we can reject the null hypothesis that *X* (independent variable) does not predict *Y* (dependent variable).
* Correlation is significant at the 0.05 level (two-tailed).
** Correlation is significant at the 0.01 level (two-tailed).

Table 3 Relationship between NDVI and RDVI indices and different curve estimation methods.

Method	NDVI				RDVI			
	R^2	df	*F*	Significant level	R^2	df	*F*	Significant level
Linear	0.517	38	40.7	0.000	0.637	38	66.58	0.000
Inverse	0.524	38	41.85	0.000	0.591	38	55.00	0.000
Quadratic	0.553	37	22.92	0.000	0.659	37	35.70	0.000
Cubic	0.558	36	15.12	0.000	0.663	36	23.57	0.000
Compound	0.399	38	25.19	0.000	0.505	38	38.73	0.000
S	0.281	38	14.85	0.000	0.337	38	19.31	0.000
Growth	0.399	38	25.19	0.000	0.505	38	38.73	0.000
Exponential	0.399	38	25.19	0.000	0.505	38	38.73	0.000

low vegetation cover in the study area, this index is not saturated. As is shown in Table 3, many linear and nonlinear relations between NDVI and vegetation cover fraction have been assessed. Similar to results obtained by Haboudane et al. (2004), the most correlation coefficient is obtained by nonlinear relations. Also, the results show that by normalization of DVI index and developing NDVI index, the correlation coefficient is reduced from 0.817 to 0.719. Regards to Table 2, the correlation coefficient of SR index is more than NDVI index.

6.2. Corrected and modified conventional indices

Regards to nonlinear relation between vegetation cover fraction and NDVI, two new indices of RDVI (Rougean and Breon, 1995) and MSR (Chen, 1996) have been proposed based on linearization of the relation between vegetation cover fraction and vegetation indices. Although MSR index is more sensitive to vegetation cover fraction, but regards to Table 2, the sensitivity of MSR index is lower than its derivative index (SR). Regards to Table 3, the correlation of determinations between MSR and vegetation cover fraction are 0.517, 0.553 and 0.558 for linear, quadratic and cubic relations, respectively. RDVI index that was developed based on modification of NDVI has the highest correlation coefficient in this class. The correlation of determinations between RDVI and vegetation cover fraction are 0.637, 0.659 and 0.663 for linear, quadratic and cubic relations, respectively. However, as Rougean and Breon (1995) notified, the results show that the relation between RDVI index and vegetation cover fraction is more linear than the relation between MSR and vegetation cover fraction. NDVIc and GNDVI indices that are based on modifications of NDVI, have lower correlation of determinations than NDVI and it seems that using green band in the sparse vegetated areas decrease the sensitivity of vegetation index to vegetation cover fraction variations. In this class, NLI index has the least correlation of coefficient. Regards to low vegetation cover in the study area and so high reflectance of soil in the near infrared range (Fig. 5), by squaring the near infrared reflectance, the sensitivity of NLI index to vegetation cover fraction variations has been reduced.

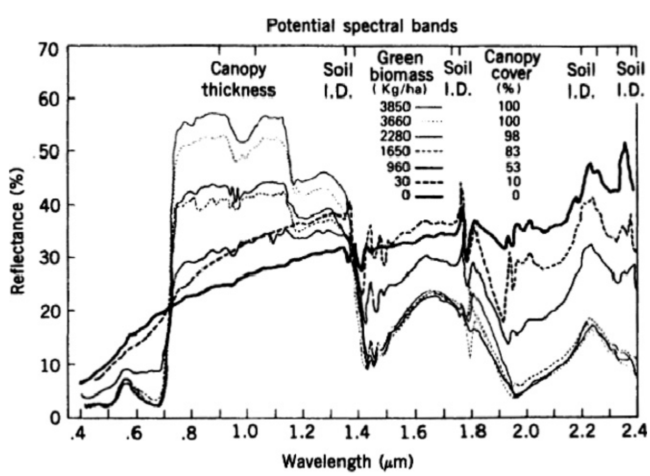

Figure 5 Reflection amounts in different spectral bands (Elachi and VanZyl, 2006).

6.3. Soil reflectance adjusted indices

In order to reduce the effects of background, Huete (1988) proposed the SAVI index. In the equation of this index (Table 1), L is a function of vegetation cover density. In this research, average of vegetation cover fraction in all sampling sites has been used to estimate L parameter and $L = 0.86853$ has been obtained. As is shown in Table 2, the correlation of coefficients of NDVI and SAVI are nearly the same. $L = 0.5$ has been considered by Huete (1988) as optimum value of L, but the correlation coefficient was not improve sensibly. It is because by using an unique L value for all the sites, the results will not improve (Huete, 1988). The same result has been obtained by using OSAVI and the correlation coefficient of NDVI, SAVI and OSAVI are nearly similar. Therefore, previous knowledge of vegetation cover is necessary to determine accurate L (Huete, 1988). To solve this problem, Qi et al., 1994 proposed MSAVI index. However, the results of this research show that correlation coefficient obtained from MSAVI index is lower than correlation coefficient of SAVI index. Generally, as Lawrence and Ripple (1998) were shown, none of these indices are more accurate than NDVI for estimation of vegetation cover fraction in sparse vegetated areas. In their studies, the correlation of determinations obtained from SAVI, OSAVI and MSAVI were 0.55, 0.59 and 0.55, respectively. However, the correlation of determination they were obtained by using NDVI was 0.62. Also, in the study had done by Baugh and Groeneveld (2006), it was shown that SAVI and MSAVI indices had inaccurate correlation of determinations of 0.4306 and 0.4446 with antecedent precipitation.

6.4. Triangular indices

The interesting result obtained in this research is that the accuracy decrease sensibly by using indices that are based on green band. This can be seen in the results obtained by GNDVI, TVI, MTVI1 and MTVI2. The last three mentioned triangular indices had been recommended for hyperspectral sensors (Haboudane et al., 2004) and maybe it is necessary to customize them when multispectral sensors are used.

6.5. Non-conventional ratio and differential indices

CI and NCI indices had been proposed to linearism the relation between vegetation biophysical parameters and vegetation indices (Vescovo and Gianelle, 2008). Regards to Table 2, these two indices are the least accurate indices. In their equations, near infrared and green bands are replaced by short wave infrared and red bands, respectively. Therefore, by using green band, the accuracy reduces. NDII index had been proposed to estimate vegetation water content (Hardisky et al., 1983). This index is based on NDVI modification and red band is replaced by short wave infrared. However, due to low water content of vegetation in the study area, the accuracy obtained from this index is not high. SLAVI index had been proposed to estimate specific leaf area (Lymburner et al., 2000). This index is based on short wave infrared band and it is the only index in this class of indices that its correlation coefficient is near the correlation coefficient obtained by using NDVI. Generally, by using short wave infrared band, the accuracy of determining vegetation cover fraction is reduced.

In order to improve the confidence of geometric correction, the accuracy assessment has been repeated by using adjacent pixels of the central pixel. The correlation coefficients between RDVI and DVI indices of these pixels and vegetation cover fraction are shown in Tables 4 and 5.

The results show that for both of the two indices, the correlation of coefficients of central pixels are more than the correlation of coefficients of adjacent pixels. This shows that the geometric correction of the image is accurate.

7. Discussion

In this research, the relations between 20 vegetation indices and vegetation cover fraction have been assessed. DVI and RDVI have the most sensitivity to vegetation cover fraction variation. Although according to results of some studies (Carlson and Riziley, 1997) NDVI is a proper index to estimate vegetation cover fraction, but the relation between this index and vegetation cover fraction is nonlinear (Haboudane et al., 2004) and also this index is not accurate in shrub lands and

Table 4 Correlation coefficient between DVI and vegetation cover fraction in the adjacent pixels.

West pixel	East pixel	South pixel	North pixel	Central pixel	DVI Index	
0.687**	0.765**	0.789**	0.666**	0.817**	Correlation	Vegetation cover fraction
0.000	0.000	0.000	0.000	0.000	Coefficient	
40	40	40	40	40	Significant level number	

** Correlation is significant at the 0.01 level (two-tailed).

Table 5 Correlation coefficient between RDVI and vegetation cover fraction in the adjacent pixels.

West pixel	East pixel	South pixel	North pixel	Central pixel	RDVI Index	
0.749**	0.754**	0.775**	0.719**	0.798**	Correlation	Vegetation cover fraction
0.000	0.000	0.000	0.000	0.000	Coefficient	
40	40	40	40	40	Significant level number	

** Correlation is significant at the 0.01 level (two-tailed).

Table 6 The regression models and their statistics.

Std. error of the estimate	Adjusted R square	R square	R	Model
3.78439	0.735	0.797	0.892[a]	1
3.72287	0.744	0.797	0.892[b]	2
3.76740	0.738	0.785	0.886[c]	3
3.80874	0.732	0.773	0.879[d]	4
3.87329	0.723	0.758	0.871[e]	5

[a] Predictors: (Constant), NCI, SRc, MTVI1, NLI, NDII, DVI, SR, MTVI2, CI.
[b] Predictors: (Constant), NCI, SRc, MTVI1, NLI, NDII, DVI, SR, MTVI2.
[c] Predictors: (Constant), NCI, SRc, MTVI1, NLI, NDII, DVI, SR.
[d] Predictors: (Constant), NCI, SRc, MTVI1, NLI, NDII, DVI.
[e] Predictors: (Constant), NCI, SRc, MTVI1, NLI, NDII.

grasslands (Montandon and Small, 2008). Elmore et al. (2000) have reported that "the correlation between the vegetation cover area and NDVI index is 67% in semi-arid regions" and linear correlation of vegetation and NDVI index is 72% in our study area.

So regards to the coefficient of determination between NDVI and the vegetation cover fraction obtained in this research (0.517) it seems that NDVI is not a proper index to use in dry areas.

In the first class of indices, the accuracies of SR, NDVI and IPVI were very similar. Another point is that the indices that are based on green indices such as GNDVI, TVI, MTVI1, MTVI2, CI and NCI have the least accuracies. However, this result is not consistent with the results obtained by Baret and Guyot (1991) and Haboudane et al. (2004), but it is similar to results of some studies were done in arid areas (Khajeddin, 1995).

Also the results show that by replacing near infrared by shortwave infrared in the indices, the accuracies decrease as CI and NCI indices have the least accuracies.

Moreover, it was shown that soil adjusted indices such as SAVI, OSAVI and MSAVI have similar accuracies as NDVI, it is opposite to results of some other studies (Rondeaux et al., 1996; Huete, 1988).

Although, DVI and RDVI are the most accurate indices to determine vegetation cover fraction but their accuracies are not proper in dry and sparse vegetated areas. Therefore, multivariable linear regression models have been developed to use the effective information of different indices. The regression models and their accuracies are shown in Tables 6. Regards to Table 6, the coefficient of determination of the first and second models are 0.797 that is much better than the coefficient of determination of DVI index.

8. Conclusion

In this research, the relations between 20 vegetation indices and vegetation cover fraction have been assessed. DVI and RDVI have the most sensitivity to vegetation cover fraction variation.

Although, the indices do not have the good coefficient of determination separately, but after combining them in a multivariable mode, it is so interesting that the accuracy improve significantly. So, the developed integrated model is recommended to use in dry regions for vegetation cover fraction estimation. Moreover, by using vegetation indices that are based on green band in dry regions, the accuracies decrease and it is necessary to be careful for using such indices when climate of the study area is dry.

Acknowledgment

The authors acknowledge the Young Researchers Club of Islamic Azad University of Ardestan Branch for financial and technical support during this research and The research project entitled of "Fractional vegetation cover determination using satellite images".

References

Bagnouls, F., Gaussen, H., 1957. Les climates ecologiques et leur classification. Annals de Geographie 66, 193–220.

Baret, F., Guyot, G., 1991. Potentials and limits of vegetation indices for LAI and APAR assessment. Remote Sensing of Environment 35, 161–173.

Baugh, W.M., Groeneveld, D.P., 2006. Broadband vegetation index performance evaluated for a low-cover environment. International Journal of Remote Sensing 27, 4715–4730.

Broge, N.H., Leblanc, E., 2000. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. Remote Sensing of Environment 76, 156–172.

Brown, L., Chen, J.M., Leblanc, S.G., Cihlar, J., 2000. A shortwave infrared modification to the simple ratio for LAI retrieval in boreal forests: an image and model analysis. Remote Sensing of Environment 71, 16–25.

Carlson, T.N., Riziley, D.A., 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. Remote Sensing of Environment 62, 241–252.

Chen, J., 1996. Evaluation of vegetation indices and modified simple ratio for boreal applications. Canadian Journal of Remote Sensing 22, 229–242.

Crippen, R.E., 1990. Calculating the vegetation index faster. Remote Sensing of Environment 34, 71–73.

Elachi, C., VanZyl, J., 2006. Introduction to the Physics and Techniques of Remote Sensing. John Wiley & Sons, Hoboken, New Jersey.

Elmore, A.J., Mustard, J.F., Manning, S.J., Lobell, D.B., 2000. Quantifying vegetation change in semiarid environments: precision and accuracy of spectral mixture analysis and the normalized difference vegetation index. Remote Sensing of Environment 73, 87–102.

Emberger, L., 1955. Une classification biogeographique des climates. Recueil des Travaux du Laboratoire de Botanique, Géologie et Zoologie de la Faculté des Sciences de l'Université de Montpellier, série Botanique 7, 3–43.

Gilabert, M.A., González-Piqueras, J., García-Haro, F.J., Melia, J., 2002. A generalized soil-adjusted vegetation index. Remote Sensing of Environment 82, 303–310.

Gitelson, A.A., 2004. Wide dynamic range vegetation index for remote quantification of biophysical characteristics of vegetation. Journal of Plant Physiology 161, 165–173.

Gitelson, A.A., Kaufman, Y.J., Merzlyak, M.N., 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. Remote Sensing of Environment 58, 289–298.

Goel, N.S., Quin, W., 1994. Influences of canopy architecture on relationships between various vegetation indexes and LAI and FPAR: a computer simulation. Remote Sensing of Environment 10, 309–347.

Haboudane, D., Miller, J.R., Pattey, E., Zarco-Tejada, P.J., Strachan, I.B., 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: modeling and validation in the context of precision agriculture. Remote Sensing of Environment 90, 337–352.

Hardisky, M.A., Klemas, V., Smart, R.M., 1983. The influences of soil salinity, growth form, and leaf moisture on the spectral reflectance of *Spartina alterniflora* canopies. Photogrammetric Engineering and Remote Sensing 49, 77–83.

Houborg, R., Soegaard, H., Boegh, E., 2007. Combining vegetation index and model inversion methods for the extraction of key vegetation biophysical parameters using Terra and Aqua MODIS reflectance data. Remote Sensing of Environment 106, 39–58.

Huete, A.R., 1988. A soil adjusted vegetation index SAVI. Remote Sensing of Environment 25, 295–309.

Jiang, Z., Huete, A.R., Didan, K., Miura, T., 2008. Development of a two-band enhanced vegetation index without a blue band. Remote Sensing of Environment 112, 3833–3845.

Jordan, C.F., 1969. Derivation of leaf area index from quality of light on the forest floor. Ecology 50, 663–666.

Kallel, A., Le-Hégarat-Mascle, S., Ottlé, C., Hubert-Moy, L., 2007. Determination of vegetation cover fraction by inversion of a four-parameter model based on isoline parametrization. Remote Sensing of Environment 111, 553–566.

Karnieli, A., Kaufman, Y.J., Remer, L., Remer, A., 2001. AFRI – aerosol free vegetation index. Remote Sensing of Environment 77, 10–21.

Khajeddin, S.J., 1995. A Survey of the Plant Communities of the Jazmorian, Iran. Using Landsat MSS Data. Reading University.

Lawrence, R.L., Ripple, W.J., 1998. Comparisons among vegetation indices and bandwise regression in a highly disturbed, heterogeneous landscape: Mount St. Helens, Washington. Remote Sensing of Environment 64, 91–102.

Lymburner, L., Beggs, P.J., Jacobson, C.R., 2000. Estimation of canopy-average surface-specific leaf area using Landsat TM data. Photogrammetric Engineering and Remote Sensing 66, 183–191.

Montandon, L.M., Small, E.E., 2008. The impact of soil reflectance on the quantification of the green vegetation fraction from NDVI. Remote Sensing of Environment 112, 1835–1845.

Nemani, R., Pierce, L., Running, S., 1993. Forest ecosystem process at the watershed scale: sensitivity to remotely-sensed leaf area index estimates. International Journal of Remote Sensing 14, 2519–2539.

Qi, J., Chehbouni, A.L., Huete, A.R., Kerr, Y.H., Sorooshian, S., 1994. A modified soil adjusted vegetation index (MSAVI). Remote Sensing of Environment 48, 119–126.

Rondeaux, G., Steven, M., Baret, F., 1996. Optimization of soil-adjusted vegetation indices. Remote Sensing of Environment 55, 95–107.

Rougean, J.L., Breon, F.M., 1995. Estimating PAR absorbed by vegetation from bidirectional reflectance measurements. Remote Sensing of Environment 51, 375–384.

Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W., 1973. Monitoring vegetation systems in the Great Plains with ERTS. In: Third ERTS Symposium. NASA, pp. 309–317.

Shupe, S.M., Marsh, S.E., 2004. Cover- and density-based vegetation classifications of the Sonoran Desert. Remote Sensing of Environment 93, 131–149.

Steven, M.D., 1998. The sensitivity of the OSAVI vegetation index to observational parameters. Remote Sensing of Environment 63, 175–181.

Tucker, C.J., 1980. A spectral method for determining the percentage of green herbage material in clipped sample. Remote Sensing of Environment 9, 175–181.

Verrelst, J., Schaepman, M.E., Koetz, B., Kneubühler, M., 2008. Angular sensitivity analysis of vegetation indices derived from CHRIS/PROBA data. Remote Sensing of Environment 112, 2341–2353.

Vescovo, L., Gianelle, D., 2008. Using the MIR bands in vegetation indices for the estimation of grassland biophysical parameters from satellite remote sensing in the Alps region of Trentino (Italy). Advances in Space Research 41, 1764–1772.

Xiao, A.J., Moody, A., 2005. A comparison of methods for estimating fractional green vegetation cover within a desert-to-upland transition zone in central New Mexico, USA. Remote Sensing of Environment 98, 237–250.