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ESTIMATING LEAF AREA INDEX FOR AN ARID REGION USING SPECTRAL DATA

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ABSTRACT

Leaf Area Index (LAI) is one of the important crop parameters that can be used to assess crop conditions or drought severity. Estimating LAI for arid regions presents challenge due to the high spatial variability in precipitation and in crop canopies found in such regions. In this study, spectral reflectance of pearl millet was computed at various wavelengths and at different times during the cropping season, using a spectroradiometer. Three main indices (Normalised Difference Vegetation Index, Ratio Vegetation Index, and Perpendicular Vegetation Index) were derived from the spectral data. These indices were then correlated with the leaf area index in order to identify the index that gave the strongest relationship. A polynomial relationship, with the coefficient of correlation of 0.70, was found between LAI and NDVI indicating that NDVI is a potential index for estimating LAI for arid regions.

Key Words: Arid lands, Leaf area index, vegetation indices

RÉSUMÉ

L'indice de la surface foliaire (ISF) est une d'importants paramètres culturaux pouvant être utilisé pour évaluer les conditions des cultures ou la sévérité de la sècheresse. L'estimation de ISF en régions arides présente une contrainte due à la variabilité spatiale dans la précipitation et la canopée des cultures dans de telles régions. Dans cette étude, la reflectance spectrale du mil (*Pennisetum glaucum* [L.] R. Br.) était calculée à des longueurs d'onde variées et à des moments différents durant la saison culturale utilisant un spectroradiomètre. Trois indices principaux (l'Indice de différence de végétation normalisée, le Rapport d'indice de végétation, et, l'Indice perpendiculaire de végétation) étaient déduits des données spectrales. Ces indices étaient ainsi corrélés avec l'indice de la surface foliaire afin d'identifier l'indice ayant une plus forte relation. Une relation polynomiale avec le coefficient de corrélation de 0.70 était trouvée entre ISF et NDVI indiquant que NDVI est un indice potentiel pour l'estimation d'ISF dans des régions arides

Mots Clés: Terres arides, indice de la surface foliaire, indices de végétation

INTRODUCTION

Leaf Area Index (LAI) is defined as the area of green leaves per unit area of the ground, and is considered a critical crop parameter (Jonckheere *et al.*, 2004). A high value of LAI indicates a denser or healthier crop canopy; while a low value represents sparse and/or drier canopy. LAI, therefore, can be used to assess crop conditions or drought severity (Chaudhary, 1987). Traditionally, LAI is measured for point locations using a leaf area meter. These measurements are averaged in order to estimate LAI for an area; but the average value may be subject to significant errors depending on sampling and spatial variability in LAI. These errors tend to expand when the spatial variation in crop canopy, and hence in LAI, increases.

Arid areas experience larger spatial variation in LAI mainly due to a high coefficient of variation (sometime even more than one hundred percent) in precipitation (Kumar, 1998). With the advent of satellite remote sensing, it has become possible to improve accuracy in areal estimates of LAI; satellite data provide continuous coverage of the ground and can be used to monitor vegetation conditions for the entire field, not just for point locations.

Satellite data are acquired in multiple bands (i.e., ranges of electromagnetic wavelengths). Multiple images of the same area acquired concurrently can be combined using different mathematical operations (e.g., addition, subtraction, ratio, etc.) to generate a new image to examine crop conditions more accurately (Goward *et al.*, 1993; Huete *et al.*, 2002; Anyamba *et al.*, 2005; Silleos *et al.*, 2006). This new image is often referred to as a vegetation index (VI) image. In this study, different vegetation indices (VIs) are derived from the spectral data collected for pearl millet, an arid-region crop, using a spectroradiometer. The spectroradiometer measures reflectance (ratio of the reflected energy to incident energy) of a ground surface.

Spectral data obtained at various wavelengths were integrated in order to estimate the reflectance within the range of the wavelength used in an operational sensor - Advanced Very High Resolution Radiometer (AVHRR) onboard the National Oceanic Atmospheric Administration (NOAA) satellite. Vegetation indices have been used for estimating crop yields (Weigand and Richardson, 1990; Niwas and Sastry, 1994; Duchemin *et al*., 2006;), crop canopy (Townshend and Justice 1995; Tateishi *et al*., 1998; Leprieur *et al*., 2000), and crop coefficients (Hunsaker *et al*., 2005). Such estimations are performed by developing a statistical relationship between LAI and the parameter to be estimated. The statistical relationship tends to be well defined for moisture-sufficient or irrigated areas. However, such studies lack for arid or moisture-deficit areas.

In this paper, pearl millet of an arid region (Jodhpur district, Rajsthan, India) was selected, because it is the main staple crop of the Indian arid zone; this crop is also sown in other arid areas of Asia and Africa. The objective of the study was to compare different vegetation indices and identify one that shows the best relationship with LAI. Identifying such a relationship will help estimate LAI of pearl millet with greater accuracy and, in turn, help monitor crop conditions, crop yields, or agricultural drought more effectively for similar arid regions.

MATERIALS AND METHODS

Study area. The study area included Jodhpur district (25° 99' N to 27° 29' N latitudes and 71° 59' E to 73° 46' E longitudes) of Rajasthan State (India), which falls within the Indian arid zone. The average annual rainfall of the district is 300 mm, majority of which occurs during the monsoon season, July through September. Droughts occur frequently (twice in about five years) in this region. Pearl millet is the main staple crop of the region.

Data used. The data used in the present analysis included the spectral reflectance of pearl millet (MH-179), spectral reflectance of the bare soil, and LAI of pearl millet. Pearl millet was planted in an experimental plot at the Central Arid Zone Research Institute, Jodhpur, Rajasthan following the monsoon rains of 67.3 cm during the third week of July. The row-to-row distance was 50 cm and the plant-to-plant distance was 15 cm. No irrigation or fertiliser was applied throughout the growing season, thus keeping the experimental conditions similar to the field conditions prevalent in the region.

The spectroradiometer was mounted on a tripod-stand kept on an angle-iron-stand to raise the height of the mirror of the spectroradiometer to 2.5 m above the ground. The field of view (FOV) of the spectroradiometer was 10.2°. The spectral range of the spectroradiometer was between 450 and 1000 nanometer, which included the red (roughly 600-700 namometer) and the infrared (roughly 700 – 1000 nanometer) ranges of the electromagnetic spectrum. The spectral response of the cropped field as well as of the bare soil adjacent to the field was recorded at different wavelengths, with an interval of 50 nanometer, on different days during the crop growing period (Table 1). Reflectance was calculated as the ratio of the spectral response from the cropped (or bare) fields to that from the barium-sulfate-coated

TABLE 1. Reflectance of pearl millet and the bare soil on different dates during the crop growing season at Jodhpur, Rajasthan, India.

Wavelength (nanometer)	Reflectance (%) of pearl millet during different days after sowing							
	22	26	35	43	54	62	68	95
450	37.8	11.7	8.8	7.9	6.7	4.3	12.3	5.9
500	32.5	12.0	10.5	7.9	7.1	3.7	19.6	5.6
550	19.6	14.0	10.4	6.0	8.0	3.9	14.5	8.3
600	22.7	15.8	10.7	5.2	7.9	5.6	15.7	10.9
650	25.8	21.6	23.3	13.7	16.7	13.2	17.3	12.5
700	30.4	23.5	37.5	24.5	26.9	16.3	23.4	17.5
750	32.0	28.4	53.7	34.9	39.1	20.4	28.6	21.4
800	32.6	30.2	57.5	39.0	44.4	29.4	32.5	23.3
850	31.8	29.3	63.2	40.8	45.2	16.7	34.2	25.2
900	33.3	28.2	56.8	38.9	45.0	21.1	33.3	26.4
950	31.0	30.6	57.1	37.1	41.3	18.9	31.4	25.5
1000	34.2	27.8	57.6	36.4	36.8	20.7	32.4	27.0
	Reflectance of the bare soil							
450	16.8	16.7	14.0	11.1	16.7	10.0	15.8	13.7
500	18.6	18.5	17.1	13.2	19.1	13.6	18.6	18.9
550	24.0	23.3	22.9	17.3	25.3	16.7	23.9	25.0
600	22.5	22.0	22.3	22.4	24.6	22.2	22.6	25.0
650	26.7	26.3	26.4	21.4	28.5	25.6	26.0	27.1
700	28.8	27.5	28.1	24.5	31.7	29.1	28.7	31.0
750	29.5	29.6	29.3	25.6	32.6	29.2	31.0	30.8
800	30.0	30.2	30.0	24.4	32.6	30.4	30.0	31.6
850	30.4	30.5	29.0	23.7	33.3	30.2	29.0	31.1
900	30.5	30.8	28.4	25.0	33.8	31.7	29.2	31.9
950	31.0	30.6	28.6	24.3	32.5	30.6	28.6	31.9
1000	31.1	29.2	28.8	25.8	32.9	29.9	29.4	32.4

surface. The temporal interval between successive readings of the reflectance was about one week and depended on the availability of cloud-free weather conditions. The time for taking measurements remained between 10.00 a.m. and 12.00 noon in order to keep the data acquiring time close to the NOAA/AVHRR satellite's passing time.

The process of examining the relationship between LAI and the spectral data required estimating spectral reflectance in the red (R) and the infrared (IR) ranges of the electromagnetic spectrum.

Estimating the reflectance in the red and the infrared ranges. The reflectance data pertaining to the pearl millet and the bare soil, recorded at different wavelength and dates, are provided in Table 1. Using the reflectance data, the reflectance curves (reflectance *versus* wavelength) for pearl millet were drawn. Figure 1 presents a sample reflectance curve. The reflectance values in the R and the IR ranges were computed using a graphical integration method. The R and IR ranges selected for the derivation of VI matched those used for the AVHRR sensor that has been widely used for vegetation monitoring. The AVHRR data are available in five channels, but only the first two channels, the red (580-680 nm) and the infrared (725-1100 nm) are used to generate VIs.

The integration of the reflectance data into the R and the IR ranges of AVHRR was performed by taking a derivative (dA/dë) of the reflectance curves, where dA is the area covered under the graph between 580 nm and 680 nm (for the R

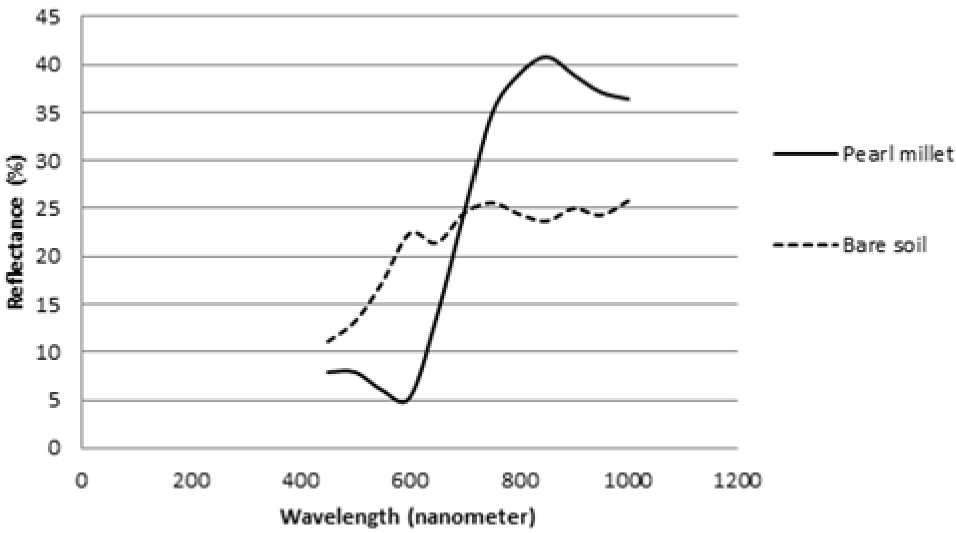

Figure 1. An example showing the variation in the reflectance of pearl millet and bare soil recorded at various wavelength at Jodhpur, Rajasthan, India.

channel) and 725 nm and 1000 nm (for the IR channel); and dë is the wavelength range of the R or the IR channel, respectively. The reflectance values, thus derived for the R and the IR ranges are provided in Table 2.

Deriving vegetation indices. Using the reflectance values of pearl millet and the bare soil in the R and the IR ranges as derived above, three main indices were generated in order to examine their relationship with the LAI of pearl millet. Such indices are derived to minimise the impact of external factors, such as canopy geometry, on their values (Baret and Guyot, 1991). The values of the indices are then mainly affected by the chlorophyll or the greenness of the canopy (Myneni *et al.*, 1995). The indices included Normalised Difference Vegetation Index (NDVI), Ratio Vegetation Index (RVI), and Perpendicular Vegetation Index (PVI), which are commonly used for vegetation monitoring. These indices are defined as follows:

NDVI = (IR - R)/(IR+R) .... (1)

where, IR and R are the reflectance in the IR and the R ranges of the electromagnetic spectrum, respectively,

RVI = IR/R, and .... (2)

PVI $\sqrt{(Rs - Rv)^2 + (IRs - IRv)^2}$..... (3)

where, the subscripts *s* and *v* refer to the soil and vegetation (pearl millet in the present case), respectively. The values of these indices, as computed above, are shown in Table 2.

LAI was measured at various phenological phases of pearl millet using an automated leaf area meter and its values are also shown in Table 2.

RESULTS AND DISCUSSION

Figure 1 shows a sample of the variation of reflectance of pearl millet at different wavelengths. It is noteworthy that the reflectance of pearl millet tends to be lowest in the red region and highest in the infrared region of electromagnetic spectrum. Hence, these two ranges are often included in generating various vegetation indices (Kirk *et al.,* 2009).

Figure 2 presents how LAI varied with time during the growing season. The variation in NDVI or RVI (Fig. 3) is similar to variation in LAI. Unlike NDVI and RVI, PVI includes reflectance of soil and, hence, the variation in PVI is distinctly

TABLE 2. The Leaf Area Index (LAI) and the values of different vegetation indices on different dates during the growing season of pearl millet in India

Date	Leaf area index	Reflectance				Vegetation indices		
		Pearl millet		Bare soil		NDVI[a]	RVI[b]	PVI[c]
		Red range	Infrared range	Red range	Infrared range			
August 13	0.60	24.0	32.3	26.48	30.2	0.15	1.35	3.25
August 17	0.90	18.8	27.6	24.3	30.7	0.19	1.47	6.31
August 26	1.97	20.0	57.0	23.5	29.0	0.48	2.85	28.22
September 3	2.51	11.4	37.7	21.9	24.6	0.54	3.31	16.79
September 14	0.79	12.0	41.9	26.0	32.9	0.55	3.49	16.64
September 22	0.35	9.0	21.5	23.9	30.2	0.41	2.39	17.25
September 28	0.16	16.6	31.9	23.5	29.3	0.32	1.92	7.37
October 5	0.07	13.0	24.8	26.6	31.5	0.31	1.91	15.16

[a]Normalised Difference Vegetation Index; [b]Ratio Vegetation Index; [c]Perpendicular Vegetation Index

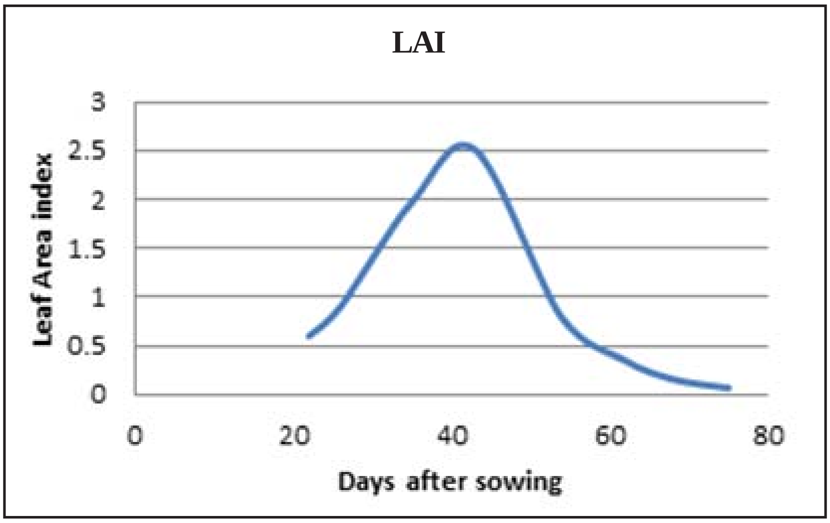

Figure 2. Variation of leaf area index (LAI) of pearl millet with the growing time.

different from that in NDVI or RVI. Increase in PVI is higher during the vegetative phase of the crop, during which leaf-area expanded fast. During this phase, reflectance from the underlying ground diminished because an increasing area of ground got covered by the leaves leading to decline in PVI as seen in Figure 3.

Figure 4 shows polynomial scatter plots drawn between LAI and various VIs. Several possible types of equations (linear, exponential, logarithmic, polynomial and power) were attempted to fit the data points of these plots. Out of the selected types of equations, the polynomial equations were found to best fit the data, on the basis of the coefficient of correlation. Besides, as shown in the Figure 4, NDVI (Coeff. Corr. = 0.70) provided a stronger relationship with LAI than did RVI (Coeff. Corr. = 0.61) or PVI (Coeff. Corr. = 0.55).

In many studies, usually for irrigated areas, the relationship between LAI and VIs is linear (Weigand and Richardson 1990; Price 1993;

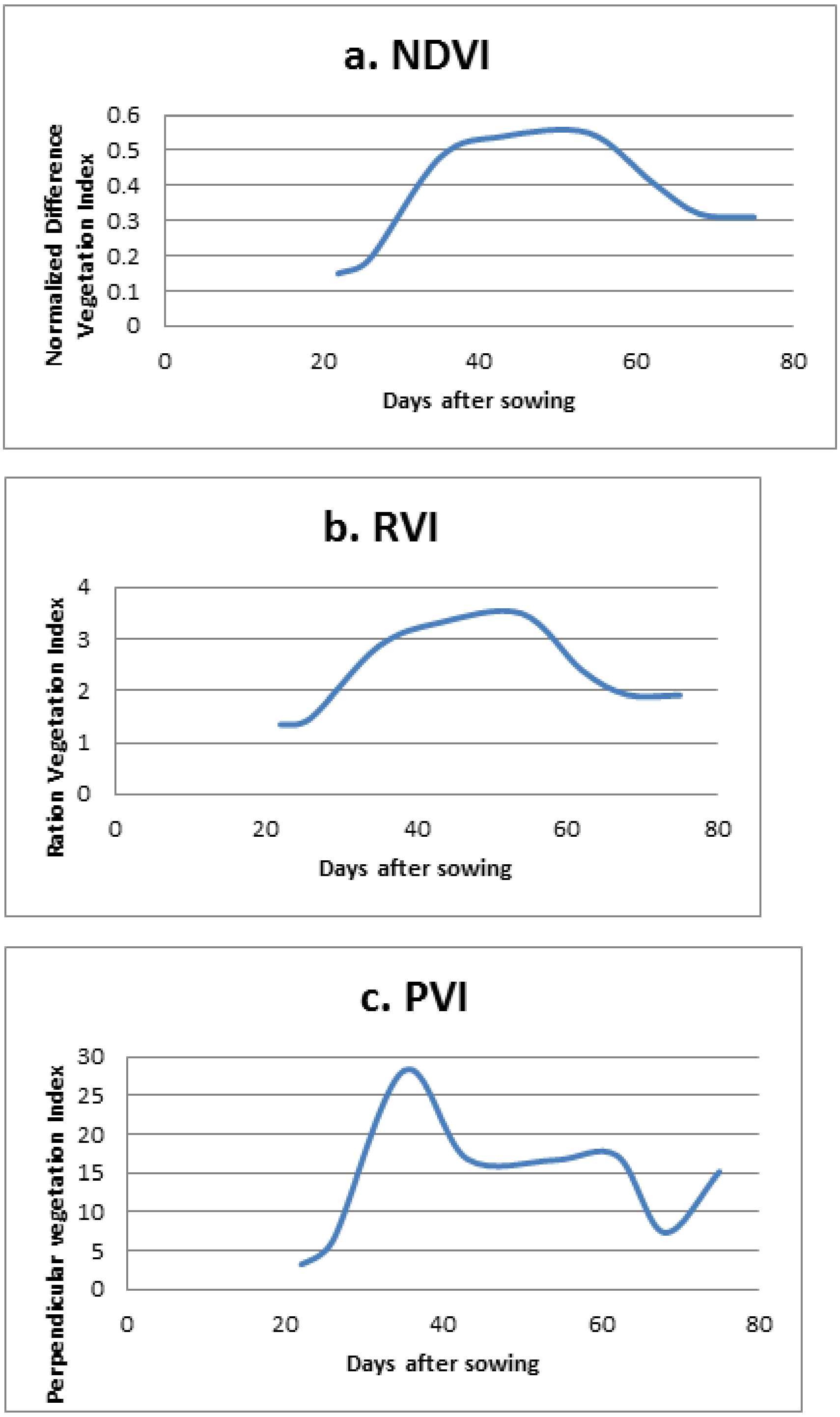

Figure 3. Variability in vegetation indices during the cropping season in India.

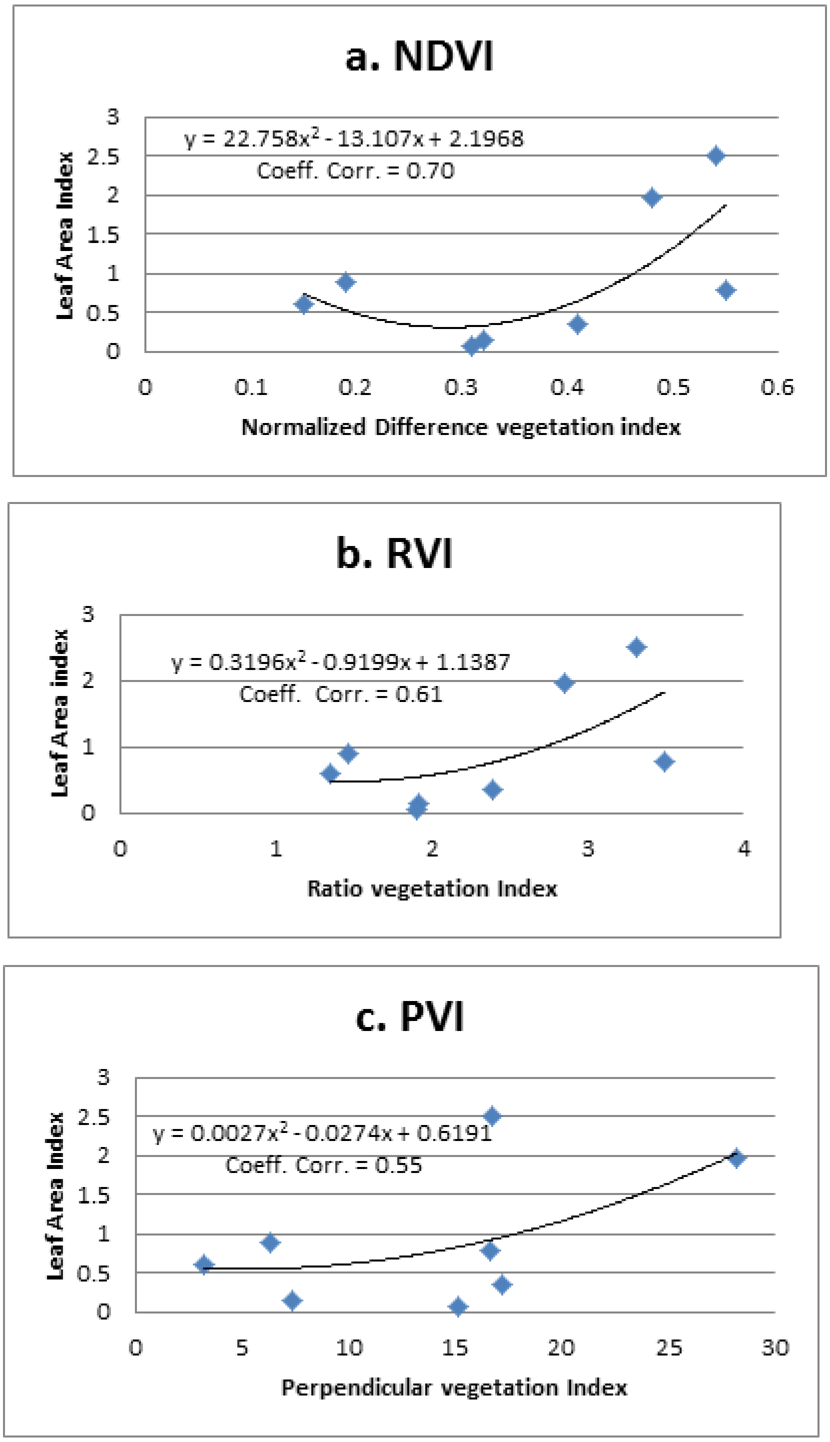

Figure 4. Relationship between the leaf area index and various vegetation indices for pearl millet grown in the Indian arid zone (Jodhpur, Rajasthan, India).

Huete *et al.*, 2002; Duchemin *et al.*, 2006). Vina *et al.* (2011) reported strong relationships between chlorophyll indices and the moderate-to-strong LAI often associated with irrigated conditions. However, a moderate relationship exists in the present case of arid conditions, apparently because of higher spatial variation in crop canopy and the higher soil reflectance in the arid region (Mand *et al.,* 2010).

The following equation explains the best possible relationship found between LAI and NDVI for the study area:

$$LAI = 22.758\,(NDVI)^2 - 13.107{*}NDVI + 2.1968 \quad \ldots\ldots (4)$$

The above relationship, however, can be further improved by involving additional data for different arid regions. Furthermore, applying NDVI fro estimating crop yield in arid regions may require great caution.

While a higher NDVI value during the vegetative phase indicates a higher amount of biomass, it is not necessary that that the higher amount of biomass results in a higher amount of yield. In arid areas, such misleading interpretations are possible due to higher spatial variability of rainfall. If an adequate amount of rainfall does not occur during the grain-filling phase that follows the vegetative phase, the yield will significantly decline despite a healthy vegetative phase. Nevertheless, a higher amount of biomass indicated by higher NDVI values could indicate a higher amount of biomass or fodder for livestock, not necessarily a higher yield.

CONCLUSION

A moderately strong polynomial relationship was found between LAI and NDVI for pearl millet grown in Jodhpur, Rajasthan, India. The relationship between LAI and other vegetation indices (RVI and PVI) was weaker. While the relationship between LAI and NDVI is often found to be linear for non-arid regions, this relationship is non-linear for arid regions requiring caution. A higher NDVI value is more likely to be an indicator of higher biomass (or fodder for livestock) which may not indicate a higher crop yield in arid regions.

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