

# COMPARISON OF ELEVEN VEGETATION INDICES FOR ESTIMATING PLANT HEIGHT OF ALFALFA AND GRASS

J. O. Payero, C. M. U. Neale, J. L. Wright

**ABSTRACT.** A great variety of vegetation indices, derived from remote sensing measurements, are commonly used to characterize the growth pattern of cropped surfaces. In this study, multispectral canopy reflectance data were obtained from grass (*Festuca arundinacea*) and alfalfa (*Medicago sativa* L.) at Kimberly, Idaho, with the purpose of comparing the performance of 11 vegetation indices for estimating plant height of these two structurally different crop canopies. An additional purpose was to develop quantitative relationships between plant height and the different vegetation indices, which could be used to estimate plant height from remote sensing inputs. For alfalfa, good logistic growth relationships between plant height and all the different vegetation indices were found. The relationship resulted in  $r^2 > 0.90$  for all the vegetation indices, and  $r^2 > 0.97$  for most of them. While all the vegetation indices were very sensitive to changes in plant height at the beginning of the growing cycle, the Normalized Difference Vegetation Index (NDVI), the Infrared Percentage Vegetation Index (IPVI), and the Transformed Vegetation Index (TVI) became insensitive to additional plant growth when alfalfa reached heights of 0.45, 0.40, and 0.45 m, respectively. All the other vegetation indices performed reasonably well for the entire range of alfalfa plant heights considered in this study ( $< 0.75$  m). For grass, on the other hand, only 4 of the 11 vegetation indices, including the Band Ratio (RATIO), TVI, NDVI, and IPVI, resulted in a reasonably good linear relationship with plant height ( $r^2 \approx 0.76$ ).

**Keywords.** Grass, Alfalfa, Remote sensing, Vegetation index, Plant height.

Vegetation indices are mathematical transformations, usually ratios or linear combinations of reflectance measurements in different spectral bands, especially the visible and near-infrared bands. They are widely used in remote sensing practice to obtain information about surface characteristics from multi-spectral measurements, taking advantage of differences in the reflectance patterns between green vegetation and other surfaces. Through the years, a great number of vegetation indices have been proposed, ranging from very simple to very complex band combinations (Perry and Lautenschlager, 1984; Bannari et al. 1995).

Kanemasu (1974) found that the ratio of the 545- and 655-nm reflectance from wheat, sorghum and soybean followed the seasonal leaf area index (LAI) curve for these crops and suggested using it as a benchmark for crop growth. Tucker et al. (1979) found that the red (RED) radiance measured above corn and soybean crops decreased as the season progressed, due to increased chlorophyll absorption by increased LAI. The photographic infrared (NIR) radiance, on the other hand, increased with time and LAI. They used five linear combinations of the red and infrared radiance data

as radiance normalization techniques to compensate for this variability. These transformations were later called vegetation indices. These indices included the Band Ratio (RATIO), Band Difference (DVI), Band Sum (SUM), the Vegetation Index (VI), and the Transformed Vegetation Index (TVI). They found the RATIO, the VI, and the TVI to be the most useful normalization techniques, with preference for the VI. The VI was later called the Normalized Difference Vegetation Index (NDVI).

Tucker (1979) studied different linear combinations of RED, GREEN, and NIR bands for monitoring vegetation properties such as biomass, leaf water content, and chlorophyll content. He found that the RATIO and related NIR and RED linear combinations were superior to the GREEN and RED linear combinations for monitoring vegetation. Also, the RATIO, DVI, VI, and TVI were found to be sensitive to the amount of photosynthetically active vegetation present in the plant canopy. All combinations were found to be similar for estimating the photosynthetically active biomass.

Idso et al. (1980) used the Transformed Vegetation Index "Six," calculated using Multi-spectral Scanner (MSS) bands five and six, to estimate crop yield. Holben et al. (1980) found the RATIO to be linearly and highly correlated to green leaf variables, such as leaf biomass. They also found that although the NDVI was exponentially related to green leaf variables, the asymptotic nature of the relationship would restrict its usefulness for high leaf biomass situations.

Jackson et al. (1983) compared the RATIO, NDVI, DVI, PVI, Tasseled Cap, and the Difference Difference (DD) vegetation indices for their abilities to discriminate vegetation from soil background and to detect stress. They found that none of the indices met all criteria as an "ideal" vegetation index. For example, the RATIO was insensitive to vegetation when the green cover was less than 50%, but was

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Article was submitted for review in May 2003; approved for publication by the Information & Electrical Technologies Division of ASAE in December 2003.

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the most sensitive index for high values of green cover. The NDVI was very sensitive to vegetation early in the season, but above 80% cover its sensitivity to vegetation changes decreased. It was also affected by soil background. Water stress, however, was not detected by any of the indices until after growth was significantly retarded.

Hatfield et al. (1984) used the Greenness Vegetation Index (GVI) to estimate intercepted photosynthetic active radiation throughout the growing season for wheat. Huete (1988) introduced the Soil Adjusted Vegetation Index (SAVI). The SAVI was derived from the NDVI as an attempt to reduce the effect of soil background on spectral data, since soil background conditions exert considerable influence on partial canopy spectra and the calculated vegetation indices.

Crippen (1990) proposed the Infrared Percentage Vegetation Index (IPVI), which was linearly equivalent to the NDVI, but had the advantage of a fully non-negative range. Wiegand et al. (1991) proposed the Transformed Adjusted Vegetation Index (TAVI), which conceptually is a measure of the angle between the soil line and the line joining the vegetation point with the soil line intercept. Thenkabail et al. (1992) defined the Stress Related Vegetation Index (STVI), obtained using LANDSAT Thematic Mapper bands three to five.

Yoder and Waring (1994) found that the sensitivity of NDVI to chlorophyll concentration varied depending on the choice of visible band used in the calculations. The visible band chosen, therefore, significantly changed the correlation between the NDVI and canopy properties. They also found that the NDVI tended to saturate as LAI increased.

Qi et al. (1994) developed the Modified Soil Adjusted Vegetation Index (MSAVI) by replacing the constant "L" value in the SAVI equation with a variable "L" function. They also introduced the Weighted Difference Vegetation Index (WDVI) and the Transformed Soil Adjusted Vegetation Index (TSAVI). They showed that the MSAVI increased the dynamic range of the vegetation signal while further minimizing the soil background influences, resulting in greater vegetation sensitivity.

Roujean and Breon (1995) tried to find an index not affected by soil reflectance and sun/view geometry. They found that soil background had a great effect on the NDVI, especially for low surface cover. The DVI was less affected by soil background than the NDVI, especially at low LAI. However, it was more affected by the spectral and directional canopy properties than the NDVI. The DVI performed better for low LAI while the NDVI was better for high LAI. Based on these observations, they developed the Renormalized Difference Vegetation Index (RDVI), combining the advantages of the NDVI and the DVI. Epiphanio and Huete (1995) described the impact of sensor view and solar zenith angles on the NDVI and the SAVI. They found that changes in view angle caused variations in the indices as high as 50%. They then introduced the Atmospherically Resistant Vegetation Index (ARVI), which included corrections for molecular scattering and ozone absorption and a function to correct the radiance in the red channel and stabilize the index to temporal and spatial variations in atmospheric aerosol content. A comprehensive review of vegetation indices has been provided by Bannari et al. (1995), who found that over 40 vegetation indices had been developed since the early 1970s.

Although a great number of vegetation indices are currently available, their usefulness in characterizing plant growth can only be realized if the appropriate index is chosen, which can be challenging. It is also vital that quantitative functions relating the index to specific plant variables are available for the surface of interest. Plant height is one of the important variables characterizing plant growth and vegetation cover, which is often needed as input for estimating energy balance components from remote sensing data (Clothier et al., 1986; Moran et al., 1989; Reicosky et al., 1994; Sene, 1994; Allen et al., 2002; Hunsaker et al., 2003). The purpose of this study was to compare the abilities of 11 commonly used vegetation indices to estimate plant height for alfalfa and grass, two structurally different canopies. An additional objective was to develop quantitative relationships to estimate plant height from remotely sensed measurements of each canopy. Establishing quantitative relationships for these two crop canopies is important since they are commonly used as reference crops for estimating evapotranspiration.

## METHODS

Data for this study were collected from adjacent grass (*Festuca arundinacea*) and alfalfa (*Medicago sativa* L.) fields near Kimberly, Idaho. The data collection period extended from June to October 1991, which included two alfalfa growing cycles. The alfalfa was of the 'Impact' cultivar, and the grass, of the 'Fawn' tall fescue cultivar. The alfalfa field was furrow-irrigated, while the grass field was flood-irrigated. The grass was clipped every week, to a height of approximately 0.09 m. The alfalfa was harvested on 2 August and on 25 September 1991.

Radiance measurements from the crops were taken approximately every other day, provided that clear-sky conditions existed. Measurements were taken between 1200 and 1400 hours, Mountain Standard Time, using a Model 100BX hand-held radiometer (Exotech Inc., Gaithersburg, Md.). The radiometer was held at arm-length, and as level as possible above the surface. The radiometer collected data in four bands, which corresponded to the LANDSAT Thematic Mapper (TM) bands TM1 (450–520 nm), TM2 (520–600 nm), TM3 (630–690 nm), and TM4 (760–900 nm). The field data collected with the radiometer were recorded using a series 700 Polycorder datalogger (Wescor, Inc., formerly Omnidata International, Inc., Logan, Utah), and then downloaded to a desktop computer for further analysis.

To standardize the radiance measurements against variations in irradiance at the time of measurement, radiance measurements were also made above a BaSO<sub>4</sub>-painted standard reflectance panel. This panel had previously been calibrated at the U.S. Water Laboratory (Phoenix, Ariz.) using a procedure described by Jackson et al. (1987). The calibration equations used to calculate the bidirectional reflectance of the panel, as a function of the solar zenith angle, in each band of the Exotech 100BX radiometer are given in table 1.

The solar zenith angle was calculated according to Duffie and Beckman (1980) as:

$$\theta_z = \cos^{-1} \{ \cos \delta \cos \phi \cos \omega + \sin \delta \sin \phi \} \quad (1)$$

**Table 1. Calibration equations to calculate the bidirectional reflectance of the panel (after Baselga, 1990).**

$$\begin{aligned} \text{Rp1} &= 1.110727 - 5.717346\text{E-}^{\text{-}03}\theta_z + 1.580958\text{E-}^{\text{-}05}\theta_z^2 - 4.847217\text{E-}^{\text{-}08}\theta_z^3 \\ \text{Rp2} &= 1.107988 - 5.774951\text{E-}^{\text{-}03}\theta_z + 2.06553\text{E-}^{\text{-}05}\theta_z^2 - 9.038902\text{E-}^{\text{-}08}\theta_z^3 \\ \text{Rp3} &= 1.100416 - 5.919145\text{E-}^{\text{-}03}\theta_z + 2.678576\text{E-}^{\text{-}05}\theta_z^2 - 1.272788\text{E-}^{\text{-}07}\theta_z^3 \\ \text{Rp4} &= 1.081548 - 5.518134\text{E-}^{\text{-}03}\theta_z + 2.339425\text{E-}^{\text{-}05}\theta_z^2 - 1.082834\text{E-}^{\text{-}07}\theta_z^3 \end{aligned}$$

where  $\theta_z$  = solar zenith angle (Deg), and Rp1, Rp2, Rp3, and Rp4 are the bidirectional reflectance of the panel in TM1, TM2, TM3, and TM4, respectively.

where

- $\theta_z$  = solar zenith angle ( $^{\circ}$ )
- $\delta$  = solar declination ( $^{\circ}$ )
- $\varphi$  = latitude ( $^{\circ}$ )
- $\omega$  = hour angle ( $^{\circ}$ )

The solar declination ( $\delta$ ) and the hour angle ( $\omega$ ) were calculated as:

$$\delta = 23.45 \sin\{(2\pi/365)(284 + \text{DOY})\} \quad (2)$$

$$\omega = (\text{ST}-\text{SN}) \times 15^{\circ} \quad (3)$$

where

- DOY = day of the year
  - ST = solar time (h)
  - SN = solar noon (SN = 12.0 h)
- The solar time was obtained from:

$$\text{ST} = \text{SDT} + [4(\text{L}_{\text{st}}-\text{L}_{\text{loc}}) + \text{E}]/60 \quad (4)$$

where

- SDT = local standard time (h)
- $\text{L}_{\text{st}}$  = standard meridian for local time zone ( $^{\circ}\text{W}$ ) (For the United States, the standard meridians are: Eastern,  $75^{\circ}\text{W}$ ; Central,  $90^{\circ}\text{W}$ ; Mountain,  $105^{\circ}\text{W}$ ; and Pacific,  $120^{\circ}\text{W}$ .)
- $\text{L}_{\text{loc}}$  = longitude ( $^{\circ}\text{W}$ )
- E = a correction term (min), obtained from the equation of time as:

$$\text{E} = 9.87\sin(2\text{B}) - 7.53\cos(\text{B}) - 1.5\sin(\text{B}) \quad (5)$$

where B is calculated as:

$$\text{B} = 360(\text{DOY}-81)/364 \quad (6)$$

Radiance data were collected using the following procedure:

1. Five dark readings. The dark readings were taken with the radiometer caps on, allowing no light to enter the lenses.

2. Five readings over the standard reflectance panel. The panel was placed horizontally and leveled using a carpenter level. Readings were taken making sure that the panel was not shaded.
3. Fifty readings from the grass field.
4. Five readings over the standard reflectance panel.
5. Fifty readings from the alfalfa field. To avoid damaging the alfalfa field, readings were taken following a consistent path within the field during the entire sampling period.
6. Five readings over the standard reflectance panel.
7. Five readings over bare soil. Measurements over bare soil were made over the same spot throughout the sampling period.

From these measurements, the average radiance for each surface was calculated. Using these averages, the bidirectional reflectance of the canopy for each of the four spectral bands (TM1, TM2, TM3, and TM4) was calculated following the procedure proposed by Bausch and Neale (1987) as:

$$\text{R}_c = [(\text{L}_c-\text{L}_d)/(\text{L}_p-\text{L}_d)] \times \text{R}_p \quad (7)$$

where

- $\text{R}_c$  = bidirectional reflectance of the canopy (unitless)
- $\text{R}_p$  = bidirectional reflectance of the panel (unitless) (calculated using equations in table 1)
- $\text{L}_c$  = canopy radiance (mv)
- $\text{L}_d$  = dark radiance (mv)
- $\text{L}_p$  = panel radiance (mv)

Eleven vegetation indices were then calculated from the reflectance data, using the equations given in table 2.

The soil line parameters needed to calculate several of the indices were determined by plotting the red reflectance (RED) versus the near-infrared reflectance (NIR) data obtained over bare tilled soil. Plant height (h) was also measured throughout the study period, on the days when radiance data were collected. Plant height for a given day represented the average of 20 measurements. Plant height at a given point in the field was measured as the average canopy height, without stretching the plants.

## RESULTS AND DISCUSSION

### ALFALFA

The crop reflectance data in the four spectral bands as a function of plant height for alfalfa are shown in figure 1,

**Table 2. Equations used to calculate the vegetation indices.**

Vegetation Index	Equation <sup>[a]</sup>	Reference
Band ratio (RATIO)	(NIR/RED)	Tucker, 1979
Normalized difference vegetation index (NDVI)	(NIR-RED)/(NIR+RED)	Tucker, 1979
Transformed vegetation index (TVI)	(NDVI+0.5) <sup>0.5</sup>	Tucker, 1979
Infrared percentage vegetation index (IPVI)	NIR/(NIR+RED)	Crippen, 1990
Perpendicular vegetation index (PVI)	[NIR-a <sub>1</sub> (RED)-a <sub>0</sub> ]/[1+(-a <sub>1</sub> ) <sup>2</sup> ] <sup>0.5</sup>	Wiegand et al., 1991
Soil adjusted vegetation index (SAVI)	[(NIR-RED)/(NIR+RED+L)] × (1+L)	Huete, 1988
Transformed soil adjusted vegetation index (TSAVI)	a <sub>1</sub> [NIR-a <sub>1</sub> (RED)-a <sub>0</sub> ]/[RED+a <sub>1</sub> (NIR)-a <sub>1</sub> .a <sub>0</sub> ]	Wiegand et al., 1991
Modified soil adjusted vegetation index (MSAVI)	(2NIR+1-[(2NIR+1) <sup>2</sup> -8(NIR-RED)] <sup>0.5</sup> )/2	Qi et al., 1994
Difference vegetation index (DVI)	NIR-RED	Roujean and Breon, 1995
Renormalized difference vegetation index (RDVI)	(NDVI × DVI) <sup>0.5</sup>	Roujean and Breon, 1995
Weighted difference vegetation index (WDVI)	NIR-a <sub>1</sub> × RED	Qi et al., 1994

<sup>[a]</sup> where NIR = crop reflectance in the near infrared band (TM4), RED = crop reflectance in the red band (TM3), L = constant (taken as 0.5) and, a<sub>0</sub> and a<sub>1</sub> are the intercept and slope of the soil line, respectively.

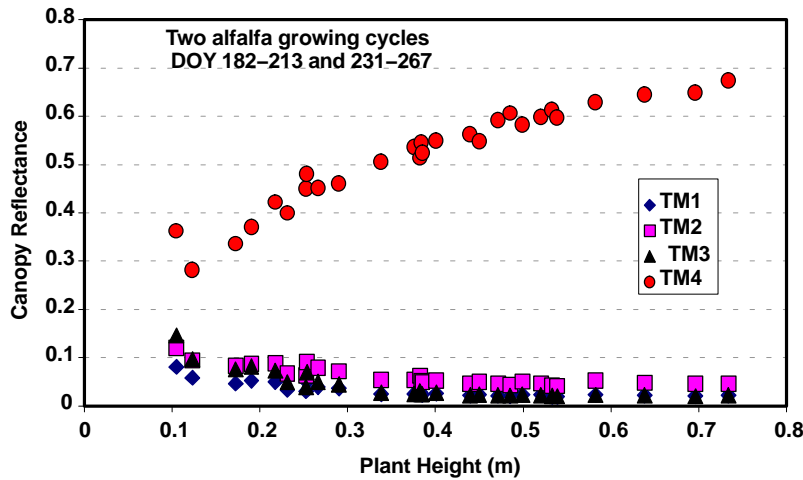


Figure 1. Canopy reflectance in four Thematic Mapper spectral bands as a function of plant height for alfalfa at Kimberly, 1991. TM1, TM2, TM3, and TM4 represent the reflectance in Thematic Mapper bands 1, 2, 3, and 4, respectively.

which includes data collected during the two alfalfa growing cycles. It shows that as plant height increased, the reflectance in the near-infrared band (TM4) steadily increased. The reflectance in the visible bands (TM1, TM2, and TM3), on the other hand, decreased with increasing plant height. These results are consistent with the fact that in the visible bands, light is absorbed by leaf pigments, mainly chlorophylls and carotenoids, while radiation in the near-infrared is highly reflected by the internal cellular structure of plant leaves (Knippling, 1970). Therefore, as biomass increases, the absorption of visible light by the increasing amount of pigments also increases, and the inverse is true for the near-infrared portion of the spectrum. These findings are consistent with those of Thomas and Oerther (1972), Rao et al. (1979), and Tucker (1978).

The reflectance in the RED and NIR bands obtained over bare soil and the resulting soil line parameters ( $a_0 = 0.0255$  and  $a_1 = 1.1351$ ) are shown in figure 2. The positive slope reflects the fact that as the soil surface dries, its color becomes lighter, which increases the reflectance in both the RED and NIR bands. The inclusion of the soil line parameters in the calculation of vegetation indices has the purpose of standardizing the effect of soil background on the crop reflectance. The purpose of this standardization is to make

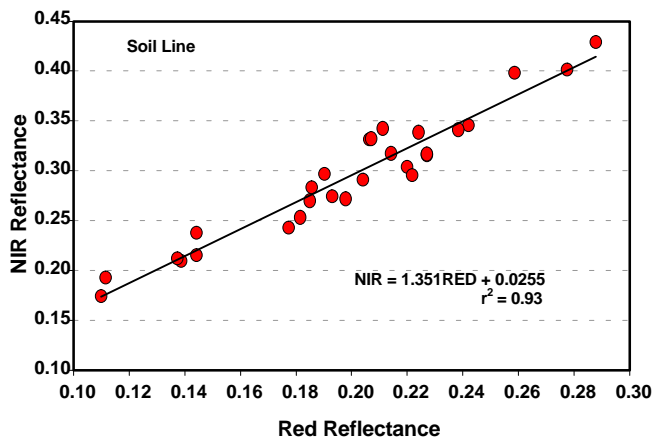


Figure 2. Relationship between RED and near-infrared (NIR) reflectance from bare tilled soil obtained at Kimberly, 1991. The slope and intercept of the regression line were used for the calculation of several vegetation indices.

the reflectance data, and the relationships derived from them, transferable to places with different soil backgrounds.

The relationship between each calculated vegetation index and plant height for alfalfa are shown in figure 3. It shows that the relationship between plant height and all the calculated vegetation indices followed a logistic growth curve. These curves were fitted to the model proposed by Arlinghaus (1994) as:

$$VI = q/(1+ae^{bh}) \quad (8)$$

where

- h = plant height (m)
- VI = vegetation index
- e = natural number
- q = empirical constant defining the upper bound of the curve
- “a” and “b” = empirical constants defining the shape of the curve

Plant height (h) can be obtained by inverting equation 8 as follows:

$$h = \text{Ln}\{[(q/VI) - 1]/a\}/b \quad (9)$$

The constants and statistics defining the relationships between the different vegetation indices and plant height for alfalfa are shown in table 3.

Figure 3 and the  $r^2$  and SEE values given in table 3 show a very good relationship between plant height and all of the calculated vegetation indices. These results suggest that for alfalfa a good relationship exists between plant height and biomass. Also, plant heights ranged between 0.10 and 0.75 m, which included a range of canopy cover conditions from almost bare soil to full canopy cover. The  $r^2$  values between measured plant heights and plant heights estimated using these vegetation indices were always greater than 0.90. Plant heights estimated using several of these vegetation indices resulted in  $r^2$  values close or even higher than 0.98. The SEE values shown in table 3 also indicate that plant height for alfalfa at Kimberly could be estimated to within about 0.02 m if a vegetation index like the SAVI is used.

Although high  $r^2$  values were obtained with all the vegetation indices, and all of them were very sensitive to increased plant height for incomplete canopy conditions, some of them showed very low sensitivity under full cover

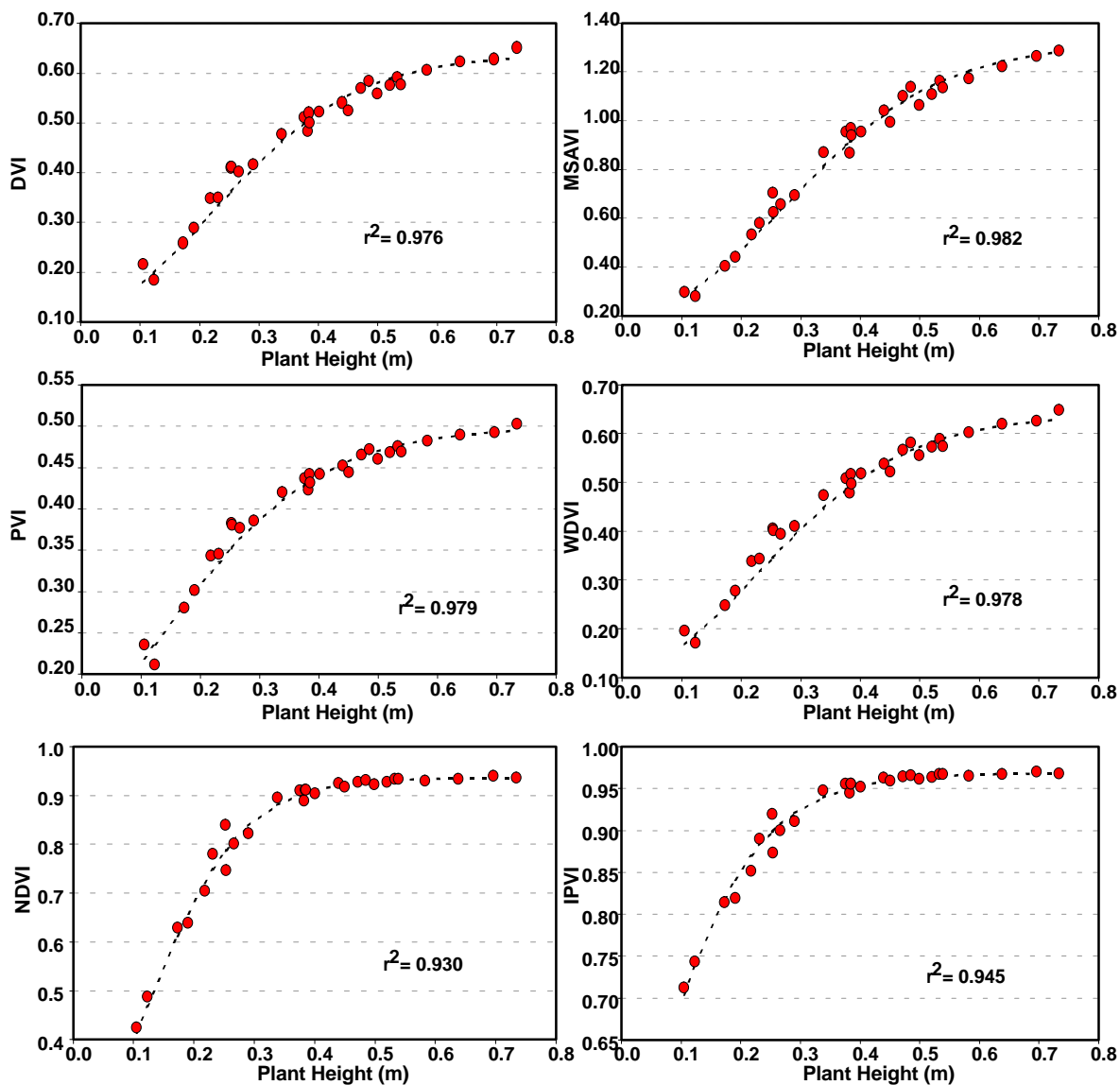


Figure 3. Relationship between different vegetation indices and plant height for alfalfa at Kimberly, 1991. Each point represents the vegetation index and plant height measured near noon for a given day.

conditions. From figure 3 it can be seen that the IPVI, NDVI, and TVI saturated at plant heights above 0.40, 0.45, and 0.45 m, respectively, and became practically insensitive to increased plant height. All the other indices performed well during the entire range of alfalfa plant heights considered in this study.

### GRASS

The canopy reflectance for grass, for each spectral Thematic Mapper band, is shown in figure 4 as a function of plant height. Since the grass was cut every week, the data represents several growing cycles. Figure 4 shows a nearly constant reflectance with increased plant height in both the visible and near-infrared spectral bands.

The apparent lack of sensitivity of the reflectance measurements with plant height for the grass surface is possibly due to several factors. First, since the grass was periodically clipped, only relatively small plant height differences are represented. Second, the grass field was

always at full cover and therefore the changes in reflectance from day to day are not as dramatic as when different proportions of vegetation and soil background are exposed, as was the case for alfalfa. Third, for grass, plant height alone is not very indicative of plant material present, since grass leaves start expanding horizontally, rather than vertically, after certain height is reached.

Even though canopy reflectance measured in the four spectral bands over the grass surface seemed nearly constant, several of the calculated vegetation indices were linearly related to plant height, as shown in figure 5. Plant height for grass could then be estimated using the equation:

$$h = a + b(\text{VI}) \quad (10)$$

where “a” and “b” are the intercept and the slope of the regression line, respectively, and VI is the vegetation index. The regression statistics for the relationship between plant height and the different vegetation indices are given in table 4

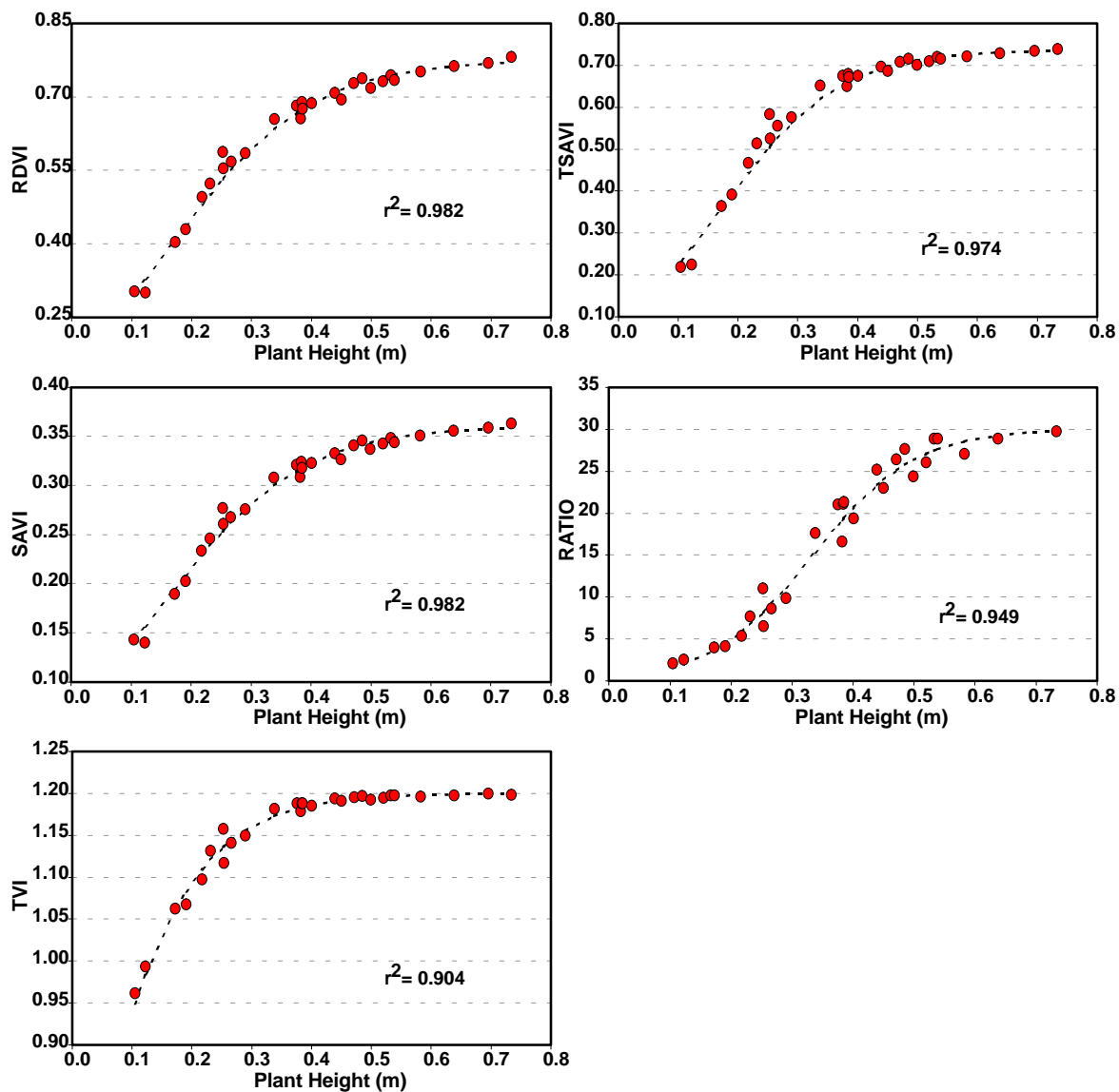


Figure 3 (continued). Relationship between different vegetation indices and plant height for alfalfa at Kimberly, 1991. Each point represents the vegetation index and plant height measured near noon for a given day.

Figure 5 and the  $r^2$  values in table 4 indicate a considerable variation in the performance of the different vegetation indices for estimating plant height for grass. The best vegetation indices for grass were the RATIO, TVI, NDVI,

and IPVI, with  $r^2$  values of approximately 0.76. The worst vegetation indices were the PVI, WDVI, and DVI, obtaining  $r^2$  values of only around 0.39. The other vegetation indices resulted in  $r^2$  values between 0.51 and 0.63.

Table 3. Empirical constants and statistics for the relationship between the eleven vegetation indices and plant height for alfalfa (SEE = standard error of estimate).

Vegetation Index	Empirical Constants in Equation 8			Statistics	
	q	a	b	$r^2$	SEE (m)
SAVI	0.361	3.813	-8.667	0.982	0.021
MSAVI	1.320	8.429	-7.686	0.982	0.022
RDVI	0.776	3.850	-8.417	0.982	0.021
PVI	0.500	2.846	-7.596	0.979	0.023
WDVI	0.640	6.529	-8.042	0.978	0.023
DVI	0.640	6.111	-8.191	0.976	0.024
TSAVI	0.737	6.370	-10.385	0.974	0.025
RATIO	30.500	49.833	-11.755	0.949	0.033
IPVI	0.968	1.152	-10.662	0.945	0.034
NDVI	0.936	4.850	-12.836	0.930	0.033
TVI	1.200	0.791	-10.443	0.904	0.052

Table 4. Regression statistics for the relationship between eleven vegetation indices and plant height for grass obtained at Kimberly (SEE = standard error of estimate).

Vegetation Index	Regression Statistics			
	Intercept	Slope	$r^2$	SEE (m)
RATIO	-0.0515	0.0106	0.765	0.016
TVI	-5.1203	4.4576	0.760	0.017
NDVI	-1.5429	1.8853	0.758	0.017
IPVI	-3.4277	3.7700	0.758	0.017
TSAVI	-0.7806	1.4046	0.633	0.021
MSAVI	-0.2502	0.4370	0.617	0.021
SAVI	-0.6376	1.1070	0.524	0.024
RDVI	-0.6093	1.1298	0.514	0.024
PVI	-0.2135	1.2740	0.393	0.027
WDVI	-0.2702	0.8399	0.394	0.027
DVI	-0.2710	0.8350	0.380	0.027

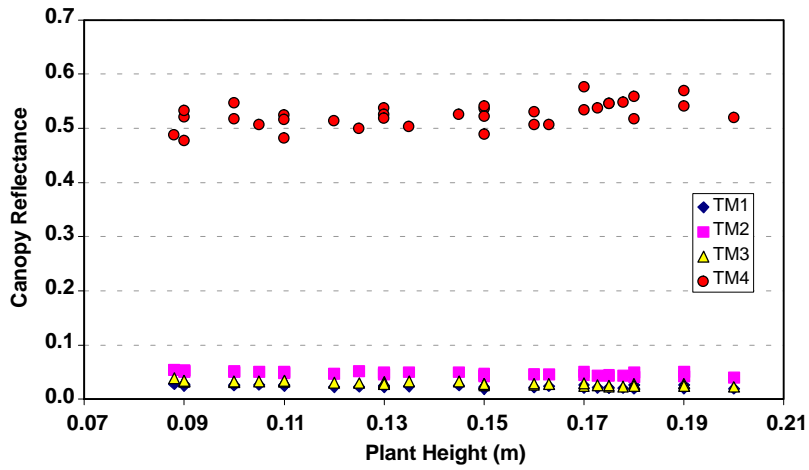


Figure 4. Canopy reflectance as a function of plant height for grass at Kimberly, 1991. TM1, TM2, TM3, and TM4 represent the reflectance in Thematic Mapper bands 1, 2, 3, and 4, respectively.

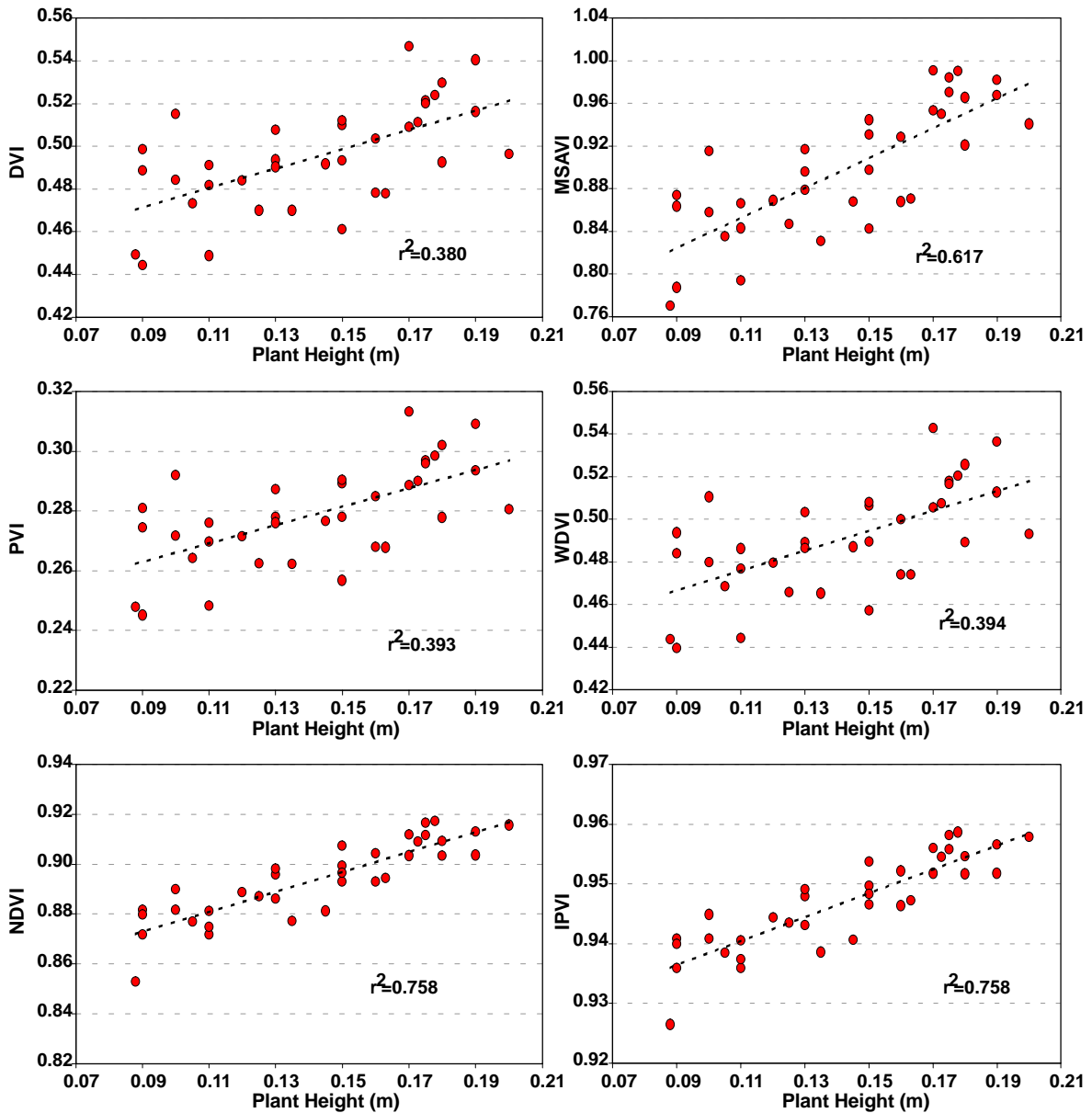


Figure 5. Relationship between different vegetation indices and plant height for grass at Kimberly, 1991. Each point represents the vegetation index and plant height measured near noon for a given day.



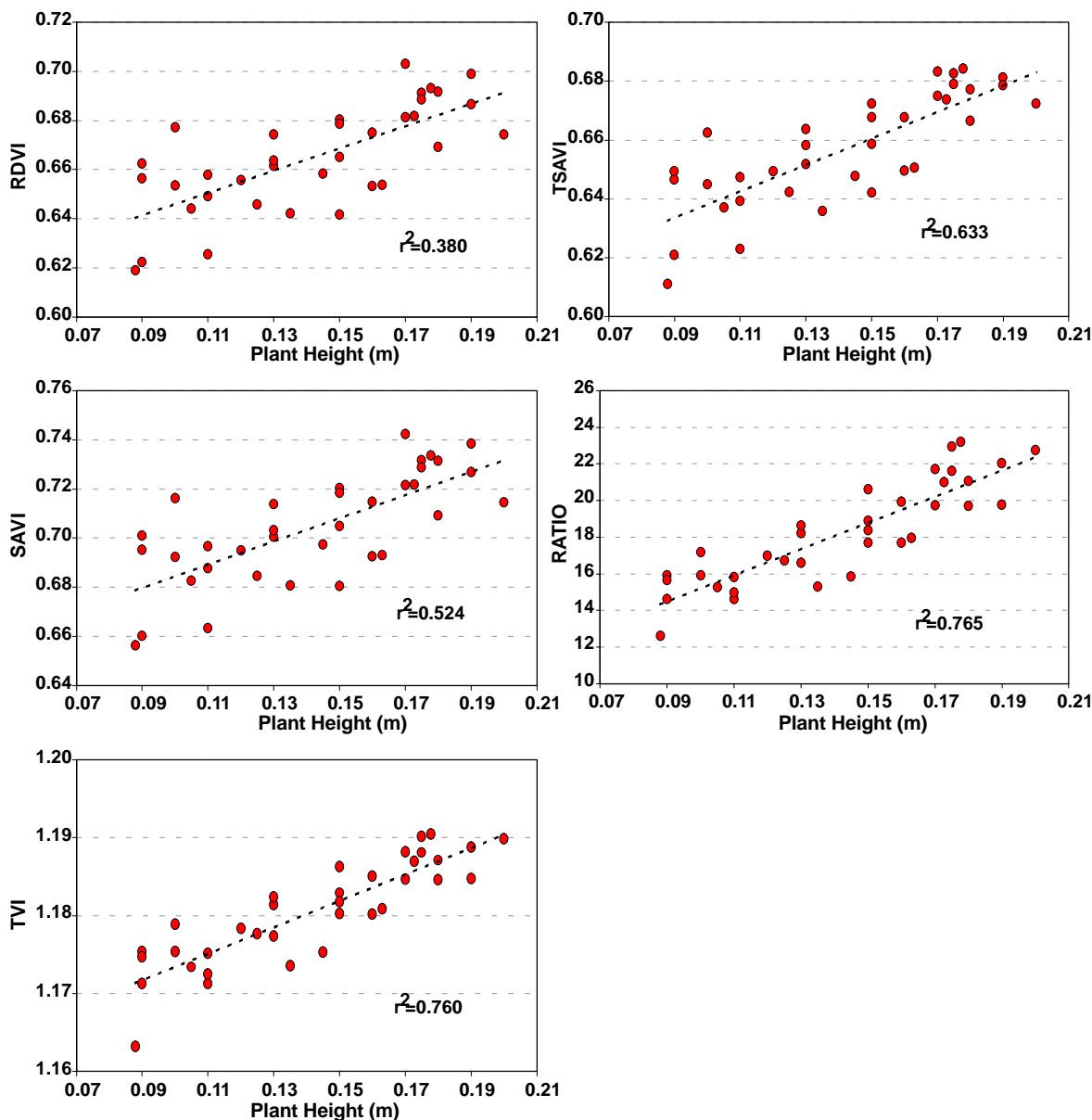


Figure 5 (continued). Relationship between different vegetation indices and plant height for grass at Kimberly, 1991. Each point represents the vegetation index and plant height measured near noon for a given day.

## CONCLUSIONS

In this study, several vegetation indices were compared for their abilities to estimate plant height for alfalfa and grass, two structurally different crop canopies. Also, empirical equations were obtained to estimate plant height using the different vegetation indices for both crops. For alfalfa, good logistic growth relationships were found between plant height and the different vegetation indices. All of the vegetation indices resulted in  $r^2$  values in excess of 0.90, and several of them, including the SAVI, MSAVI, RDVI, PVI, WDVI, DVI, and TSAVI resulted in  $r^2$  values above 0.97. All the vegetation indices tested in this study were very sensitive to increases in plant height when the alfalfa crop was less than 0.40 m in height. Above that height, several of the vegetation indices, including the IPVI, NDVI, and TVI became insensitive to additional increases in plant height.

For grass, the performance of the vegetation indices for estimating plant height was not as good as for alfalfa. Best results were obtained using a linear function and only the

RATIO, TVI, NDVI, and IPVI performed relatively well ( $r^2 \approx 0.76$ ). The results obtained in this study point out the importance of selecting the appropriate vegetation index for the particular crop and for the particular plant height being considered. These results also make it clear that when trying to estimate plant height from vegetation indices, a much higher accuracy can be obtained for a crop like alfalfa, which presents a range of cover conditions during its growing cycle, than can be obtained for grass, which is always at full cover.

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