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A New Enhanced Soil Adjusted Vegetation Index: HYBRID

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Abstract: First-order soil brightness effects are accounted for with orthogonal indices and Soil Adjusted Vegetation Indices (SAVI) and particularly true at very low Leaf Area Indices (LAI). However, they have limited dynamic range and they fail to account for residual soil brightness effects observed at intermediate LAI. The objective of the study is to devise an index from existing ones that would overcome these shortfalls. First, a graphical method is shown to give a general formulation for the orthogonal vegetation indices (i.e., ADVI). Then, from the analysis of ADVI, it is shown that ratio and orthogonal are functionally equivalent under certain conditions. Finally, by combining ADVI and SAVI, the new hybrid index (HYBRID) obtained is the least affected by soil brightness effects at all LAI values, has the greatest dynamic range, is the most sensitive to LAI changes, saturates at very high LAI and seems to evolve linearly with LAI.

Key words: Soil brightness, remote sensing, vegetation index, LAI, wheat, biomass, yield

INTRODUCTION

Vegetation indices, which are either linear or non linear combinations of visible and near infrared radiances, are at the core of the wide application of remote sensing in assessing vegetation cover, wet or dry biomass, green leaf area index, grain yield and water stress in crops (Tucker, 1979; Rudorff and Batista, 1990; Jackson *et al.*, 1983), or in determining crop nutrient requirement (Sripada *et al.*, 2006), or spatial variability in field crops (Martin *et al.*, 2007; Webster *et al.*, 1989). Among the many vegetation indices that exist in the remote sensing literature, the Normalized Difference Vegetation Index (NDVI) is with no doubt the most utilized index.

$$\mathrm{NDVI} = {(\rho_{nir} - \rho_{red})}\big/{(\rho_{nir} + \rho_{red})} \qquad (1)$$

The reported strong correlations between NDVI and biophysical variables such as yield (Martin *et al.*, 2007), vegetation cover (Clevers, 1988), green or dry biomass (Inman *et al.*, 2007; Chang *et al.*, 2005) and leaf area index (Baret and Guyot, 1991; Wiegand *et al.*, 1990) indicate the usefulness of the NDVI.

However, variability in NDVI due to changes in soil brightness had led researchers to search for less soil prone vegetation indices. Two major categories of vegetation indices in the literature are the slope (or ratio) based and the distance based (orthogonal) vegetation indices. They are both easily represented graphically on the NIR-RED spectral space.

The slope based vegetation indices: While, the NDVI falls in this group, it was the one that was adjusted by the use of an empirical soil factor, L (Huete, 1988; Qi *et al.*, 1994) to yield the Soil Adjusted Vegetation Indices (SAVI). The general formulation of the ratio indices can be written as the SAVI as follows:

$$\mathrm{SAVI} = {(\rho_{nir} - \rho_{red})}\big/{(\rho_{nir} + \rho_{red} + L) \times (1 + L)} \qquad (2)$$

Historically, SAVI index is the term used when L is set to 0.5 (Huete, 1988) while, with MSAVI (Qi *et al.*, 1994), L is an iterative value which decreases as Leaf Area Index (LAI) increases. The idea behind the L factor was to shift the origin of red-near infrared reflectance space such that vegetation isolines (points of equal LAI) converge towards a single point. The SAVI indices have been proved to reduce soil brightness effects either with simulated or measured data (Huete, 1988; Major *et al.*, 1990; Baret and Guyot, 1991; Rondeaux *et al.*, 1996).

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The distance based vegetation indices: Contrary to the slope based vegetation indices given above, the distance based vegetation indices assume that vegetation isolines are parallel to the soil line and they measure the perpendicular distance of a given point to the soil line in the red-near infrared reflectance space. Among this group are the Perpendicular Vegetation Index (PVI) Tucker (1979) and the Weighted Vegetation Indices (WDVI) (Clevers, 1988):

$$\mathrm{WDVI} = \rho_{nir} - a.\rho_{red} \tag{3}$$

$$\mathrm{PVI} = \frac{1}{\sqrt{1+a^2}}(\mathrm{WDVI} - b) \tag{4}$$

Here, the parameters a and b represent the slope and the intercept of the soil line, respectively. The DVI is just WDVI in which parameter a is set to unity and both are quite similar in magnitude. While, they both suppress soil effect at very low vegetation amounts, they are limited by a relative small dynamic range compared to the slope based vegetation indices. Hence, these indices may not be as powerful at detecting a wide range of LAI values.

The distance based indices performs less at intermediate to high LAI than the slope based vegetation indices because of their much reduced dynamic range. At this LAI range, neither category of vegetation indices seems to describe canopy spectral behavior (Huete, 1988). Thus, the main objective of the study is devise a vegetation index with improved dynamic range and which could drastically reduce soil brightness effects from low to high LAI values. The new index begins with a new generalization of the distance based indices (ADVI, Fig. 1).

MATERIALS AND METHODS

The derivation of the Area Difference Vegetation Index (ADVI): This vegetation index falls in the class of the distance vegetation indices and thus, it is assumed that vegetation isolines are nearly parallel to the soil line. Let Q be the point with coordinates (1, 1) in Fig. 1. Let also M, a given point in the NIR-RED reflectance space, be projected horizontally and vertically onto the bisect line (1:1 line, implicit soil line) to yield two new points (B and C). Each of these latter points represents the lower left corner of a square whose upper right corner is the point Q in the NIR-RED space. The smallest and the largest squares have a side of 1 minus the near Infrared Reflectance (1-NIR) and one minus the Red reflectance (1-RED), respectively. The difference between the areas of the two squares is the hashed area in Fig. 1.

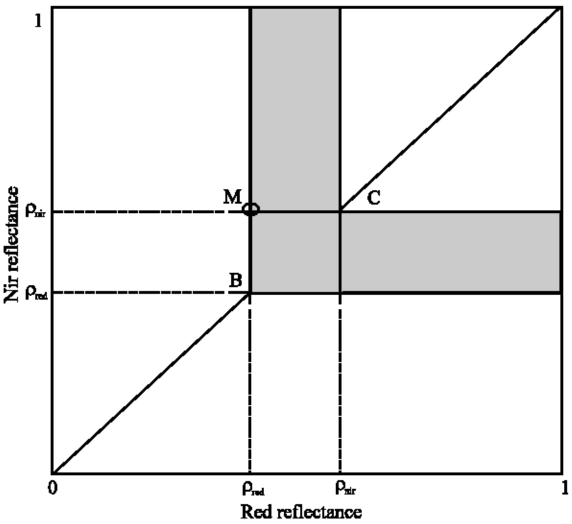

Fig. 1: The graphical derivation of in the Nir-Red spectral space. ADVI for point M is the hashed area

As LAI increases, canopy near infrared reflectance increases and point C moves towards the upper right point Q(1, 1) along the bisect line, while point B moves towards the origin. In other words, as LAI increases, the smallest square shrinks and the other one increases thus, the hashed area augments. The projections of point M onto the bisect line (i.e., points B and C) are affected by a change in soil brightness but the difference in the areas of the resulting squares is not affected as long as the assumption of parallel isolines holds. In other words, the hashed areas for two points situated on a same isoline are identical and thus, soil brightness effects are eliminated.

For a bare soil (LAI = 0), point M is on the soil line (here taken as the bisect line), the hashed area is zero, whereas at very high LAI, the hashed area tends towards one. Hence, the hashed area is the basis of the new vegetation index which accounts for soil brightness effects (Eq. 5a):

$$\mathrm{ADVI} = (1-\rho_{red})^2 - (1-\rho_{nir})^2 \tag{5a}$$

A simplified version of the index is given:

$$\mathrm{ADVI} = (\rho_{nir} - \rho_{red}) \times (2 - \rho_{nir} - \rho_{red}) \tag{5b}$$

A general formulation of ADVI: ADVI as computed above is obtained by setting the upper limit of the hashed area to 1 on both the X-axis and the Y-axis. Likewise, a more general expression for ADVI can be derived by setting this upper limit to A, an arbitrary value. The new point Q is Q(A, A) in Fig. 1. Still, the hashed area is computed but it must be normalized to have ADVI constrained between -1 and 1. The normalizing factor is given by the reciprocal of the maximum value taken by the hashed area, which is reached when near infrared reflectance is unity and red reflectance is zero. Hence, the general formulation of the orthogonal indices will be referred to as the ADVI:

$$\mathrm{ADVI} = \frac{(A-\rho_{red})^2 - (A-\rho_{nir})^2}{2A-1} \tag{6a}$$

Or when simplified;

$$\mathrm{ADVI} = (\rho_{nir}-\rho_{red}) \times \frac{(2A-\rho_{nir}-\rho_{red})}{2A-1} \tag{6b}$$

Equation 5b (A = 1) is a special case of Eq. 6b. If the value of A becomes very large (i.e., A tends towards ∞), ADVI is reduced to the Difference Vegetation Index (DVI). In general, raising the value of A lowers the magnitude of the vegetation index as long as the sum of red and near infrared reflectance values does not exceed one. This is the case for photosynthetically active tissues, which are characterized by high near infrared and low red reflectance values.

Efficacy of the ADVI in reducing soil brightness effects: what is the best A value?

Case 1: When A is a constant value: Since, A is arbitrarily chosen, what value provides an AVDI that best minimizes soil brightness effects at all LAI values. From simulation scenarios, the optimum ADVI is given by Eq. 5 in which A is unity. This ADVI is compared with SAVI for different soils (Fig. 2a, b vs. 3a, b) and leaf optical properties of Fig. 2a, b or 3a, b). Figure 2 and 3 the difference in vegetation index response of canopies of equal vegetation amounts under two soil background conditions (a bright soil and a dark soil) is used to assess soil background effects. The DVI is also included to show that large values of A are less desirable. For all combinations of soil parameters and leaf optical properties chosen, SAVI outperforms the best ADVI at all vegetation amounts. Hence, it can be tentatively concluded that the slope based are superior to the distance based vegetation indices.

Case 2: A is chosen so that ADVI and SAVI match: When parameter A is held constant in ADVI, SAVI outperforms ADVI. However, since the value of A is arbitrary, it can be allowed to change with vegetation amount just like the L factor in SAVI is made to vary. Upon inspection of Eq. 2 and 6b, it appears that both vegetation indices are equivalent if the parameter A in ADVI is chosen such that:

$$A = \frac{\rho_{nir}+\rho_{red}+1+L}{2} \tag{7}$$

This equation establishes the functional equivalence of both vegetation index categories. Moreover, for ADVI to perform as well as the SAVI the parameter A in ADVI must not be constant during the cycle of the crop. When L = 0.5, the expression of (Eq. 7) is linearly dependent upon canopy spectral reflectance values. SAVI (L = 0.5) is limited by its low dynamic range because the L factor is much greater than the spectral reflectance values. Hence, SAVI needs further improvement.

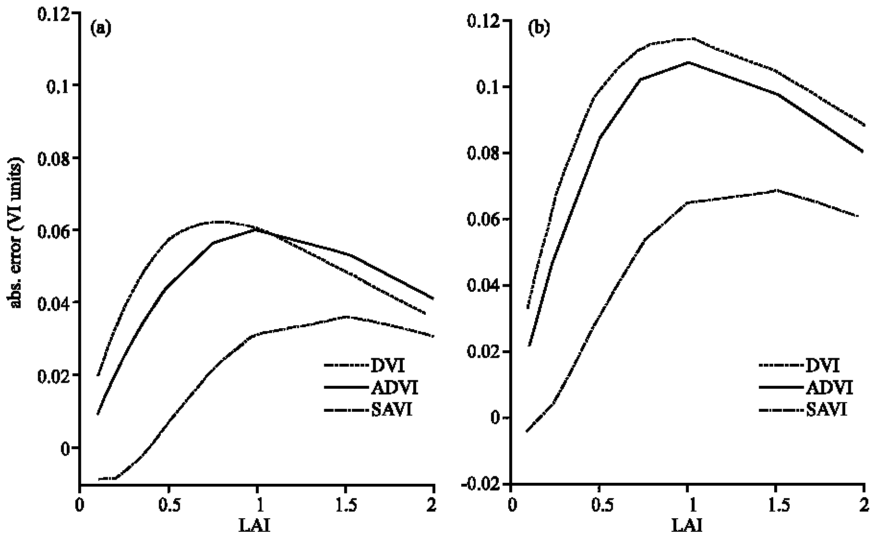

Fig. 2: Difference in VI response at two brightness levels for the ideal soil (a = 1.0 and b = 0.0)

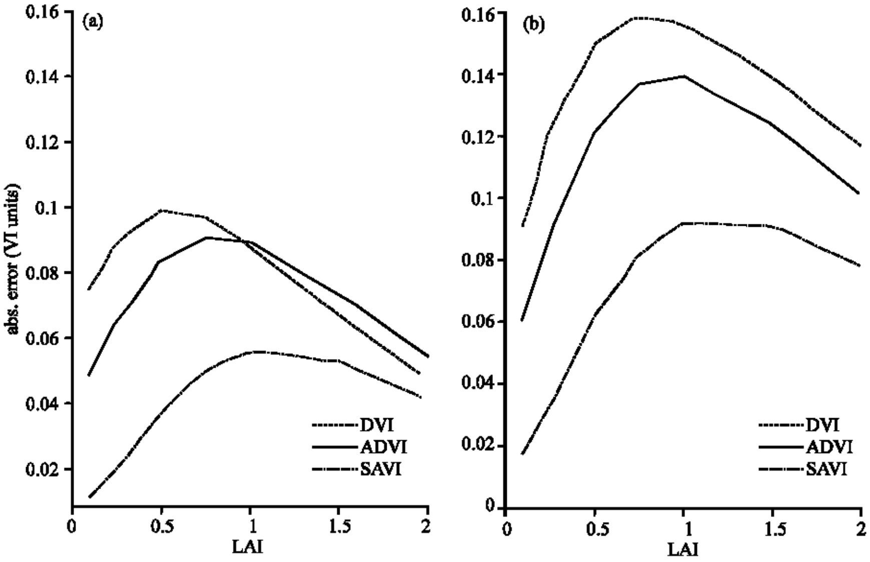

Fig. 3: Difference in VI response at two brightness levels for a soil (a = 1.2 and b = 0.04)

The limitation of existing vegetation indices was noted by Huete (1988) who observed that for vegetation conditions between sparse and dense canopies, neither the ratio nor the orthogonal can adequately describe incomplete canopy spectral behavior. In fact, some residual soil brightness effects remain for LAI between 0.5 and 2, regardless of the index chosen (Fig. 2a, b or 3a, b). This residual soil effect increases with the soil line slope (Fig. 2a, b vs. 3a, b) and is also affected by the optical properties of the leaf (Fig. 2a, b vs. 3a, b). For example, the absolute error in SAVI units at LAI of unity (LAI = 1.0) increases from 0.03 (Fig. 2a, b) to about 0.06% (Fig. 3a, b) when soil line slope changes from 1-1.2. When single leaf spectral reflectance has a high contrast with non living materials, soil brightness effects are amplified (Fig. 2a, b or 3a, b). The residual soil brightness effects peak at LAI between 1 and 2.

Case 3: Find A such that residual soil brightness effects are reduced in ADVI: We hypothesized that if residual soil brightness effects exist in SAVI, then the expression of A (Eq. 7) that transforms ADVI into SAVI is not optimized. Since, first-order soil brightness effects seem well reduced in SAVI, its corresponding parameter, A (Eq. 7) could be a starting point in the quest for the optimal value for parameter A. The low dynamic range of SAVI indicates that A (Eq. 7) is greater than the optimal value. The best value of parameter A which yields the best results is the cube of Eq. 7:

$$A = \frac{(\rho_{nir} + \rho_{red} + 2 - SAVI)^3}{8} \qquad (8)$$

The soil factor, L, in SAVI is replaced by the term 1-SAVI and SAVI with L set to 0.5 is used. All in all, the new vegetation index (HYBRID) that best minimizes soil brightness effects (first and second order terms) can be computed in three steps:

Step 1: Compute SAVI (Eq. 2 with L = 0.5).

Step 2: Compute A as in Eq.8.

Step 3: Compute HYBRID as in Eq. 6b.

This three step approach is a substitute to the lengthy and complex expression of the hybrid vegetation index given in Eq. 9.

$$\text{HYBRID} = \frac{W - 4(\rho_{nir} + \rho_{red})}{W - 4}(\rho_{nir} - \rho_{red}) \qquad (9)$$

With

$$W = \left[\frac{(\rho_{nir} + \rho_{red})^2 + \rho_{nir} + 4\rho_{red} + 1}{\rho_{nir} + \rho_{red} + 0.5}\right]^3$$

Model data used to test the new vegetation index: The Goudriaan (1977)'s model has been used to analyze the effect of soil brightness on ADVI since it gives an analytical solution to the radiative transfer equation for canopies with horizontal leaf angle distribution. Canopies dominated by horizontal leaf angle distribution have a spectral response which is less dependent on solar direction (Pinter *et al.*, 1985). Hence, directional and soil brightness effects can be decoupled in the analysis.

Table 1: Crop and soil data used for model simulation

	Spectral domain	
Properties	Red band	Nir band
Leaf reflectance: leaf1 (leaf2)	0.10 (0.05)	0.40 (0.44)
Leaf transmittance: leaf1 (leaf2)	0.10 (0.02)	0.40 (0.54)

Soil reflectance: 0.05 (dark soil) and 0.35 (bright soil) for the red band; Soil line parameters: soil 1 (slope = 1.0; intercept = 0.0); soil2 (slope = 1.2; intercept. = 0.04); LAI = 0.10, 0.25, 0.50, 0.75, 1.0, 1.50, 2.0; Leaf angle distribution function: Horizontal

Measured data: Crop and soil optical properties used are summarized in Table 1. It is also important to assess the performance of the HYBRID with measured crop spectral data. Red and near infrared reflectance factors and LAI of winter wheat (*Triticum aestivum* L., var Madsen) measured in an experimental field during the 1989-1990 growing season in Pullman, WA are available. Spectral measurements were made under clear, sunny sky conditions and from a two-band handheld radiometer built from an unused SLR camera.

RESULTS AND DISCUSSION

SAVI outperforms ADVI (when A is held constant) in terms of soil brightness effect reduction capability regardless of leaf optical properties and soil type. Next, if parameter A in ADVI is judiciously chosen as in Eq. 7, SAVI and ADVI are just identical. Finally, the HYBRID is supposed to provide a further improvement over the SAVI by reducing residual soil brightness effects observed at intermediate vegetation amounts.

As shown in Fig. 4, the HYBRID not only reduces residual soil effects for LAI between 1 and 2 but it is the least affected at very low LAI values. For example, at LAI of 1.0, absolute error in VI units is 0.005 and 0.035 for HYBRID and SAVI, respectively. The substantial improvement of HYBRID over SAVI occurs for LAI <2 and beyond this value, none of the indices is seriously affected by soil background effects.

Sensitivity of vegetation indices to leaf area index: The variation of vegetation indices (NDVI, SAVI and HYBRID) during the growing season of a winter wheat is shown in Fig. 5. The NDVI displays its usual exponential curve as it quickly saturates at moderate vegetation amounts. The SAVI shows a slight but steady increase with LAI. The new hybrid vegetation index displays the maximum sensitivity to LAI increases from moderate to high vegetation amounts. This characteristics may partly be due to the fact that it efficiently removes (first or second orders) soil brightness effects and hence, subtle increases in LAI are effectively sensed. While at low LAI values, HYBRID mimics the SAVI index, it tends towards the NDVI at very high LAI. Unlike the NDVI it only saturates at very high LAI, a feature which would make the HYBRID particularly useful in vegetation monitoring and biomass assessment and particularly so in very dense forest canopies. When LAI is not high enough, the dynamic range of HYBRID over SAVI is dismal.

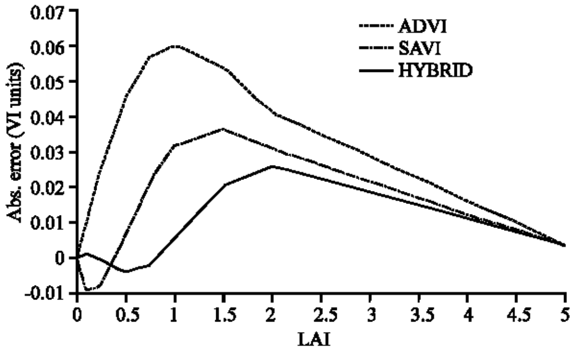

Fig. 4: Soil brightness effects in three vegetation indices as a function of LAI

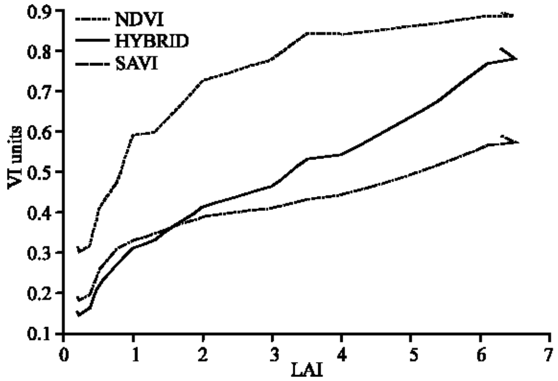

Fig. 5: Vegetation response as a function of LAI

The other advantage of the HYBRID index over existing ones is its near linear response to leaf area index (Fig. 5). This particular trend is explained by the fact that at low LAI it is similar to SAVI and gradually evolves towards NDVI at very high LAI. However, more testing with robust radiative transfer models such as the SAIL (Verhoef, 1984) and with measured data from different crops is needed to further substantiate the interesting features this new index offers.

CONCLUSION

The issue of soil brightness effects on vegetation indices is revisited. First order soil brightness effects are accounted for by distance based vegetations and even better by the known ratio vegetation indices. However, both fail to account for residual soil effects which seem more important at intermediate vegetation amounts.

To account for this residual soil brightness effects, HYBRID, a hybrid vegetation index between the orthogonal and the ratio indices, has been devised. Preliminary work with simulated and measured shows promising results with the HYBRID index. It does not saturate as fast as the NDVI, has a great dynamic range, is very sensitive to LAI over a large spectrum of LAI values and shows a linear response to LAI increase. However, the only drawback of the index may be its cumbersome expression compared to ordinary vegetation indices.

Soil brightness is just one among the many extraneous factors that affect canopy reflectance; hence, the HYBRID index needs an extensive analysis before it can be widely used for remotely sensing vegetation status and content.

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