SHORT COMMUNICATION

MODIS NDVI Optimization To Fit the AVHRR Data Series—Spectral Considerations

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In early 1999, about when this article will hit the press, NASA is scheduled to launch its first Earth Observing satellite System (EOS) with array of instruments for precise, scientific, remote sensing of the Earth land, ocean, and atmospheres. One of the main instruments, MODIS, will monitor daily vegetation dynamics with seven specially selected and highly characterized and calibrated spectral channels in the solar spectrum, with spatial resolution from 250 m to 500 m. These MODIS data, together with multiangular observations from the MISR instrument (also on EOS), will generate a much better picture of vegetation dynamic than previous satellite data records. But studying changes on the Earth surface takes years and decades. To do it in our scientific lifetime, there is a need to be able to develop a data series that combines the traditional NDVI-AVHRR data sets that was used to monitor vegetation dynamics with the new MODIS data with its narrower channels. Here we propose that due to spectral difference between the AVHRR and MODIS, a combination of the MODIS red and green channels should be used to represent the AVHRR red channel in such long term data series, to avoid a step in the NDVI of δNDVI of up to 0.05. We use both leaf spectra and full canopy spectra to develop and test this optimization. Optimization of the MODIS sensitivity for monitoring the dynamics of vegetation chlorophyll content is also discussed. ©Elsevier Science Inc., 1998

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INTRODUCTION

The physical and physiological parameters of vegetation (leaf area, biomass, physiological functioning, etc.) may be obtained from satellite remote sensing. For these reasons, several of the instruments scheduled to fly on the Earth Observing System are designed for land surface studies (Asrar and Dokken, 1993). These instruments measure solar radiation reflected by vegetation and soils at certain wavelength bands. Several indexes were developed for remote estimates of various vegetation parameters. The broadband red (0.60–0.70 μm) and near-infrared (0.75–1.35 μm) channels have been found to be most valuable in remote sensing of vegetation. Indexes that use these spectral channels were suggested for remote estimates of vegetation dynamics (Tucker, 1979), fraction of absorbed photosynthetically active radiation (Asrar et al., 1984), unstressed vegetation conductance, and photosynthetic capacity (Sellers et al., 1992). They were used to estimate the effect of vegetation on seasonal atmospheric carbon dioxide variations (Tucker et al., 1986) and the effect of CO_2 and temperature change on the vegetation (Myneni et al., 1997a). Myneni et al. (1995) showed that for dense vegetation, the widely used broadband red/near-infrared vegetation indexes are a measure of chlorophyll abundance and energy absorption. Therefore, for proper application of vegetation indexes, it is important to investigate the sensitivity of the vegetation reflectance in different spectral channels to chlorophyll (Chl) content.

Recently, it was found that the sensitivity of NDVI to moderate to high Chl content (white-green to dark-green vegetation) is small because the reflectance in spectral region near 670 nm saturates for low Chl content (Buschmann and Nagel, 1993; Gitelson and Merzlyak, 1994 a,b; 1996; Yoder and Waring, 1994; Gitelson et al., 1996; Myneni et al., 1997b). Thus, NDVI is sensi-

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tive to low Chl content, to the fraction of vegetation cover, and, as a result, to the absorbed photosynthetically active solar radiation. But it is not sensitive to Chl at higher chlorophyll content, and rate of photosynthesis for large vegetation coverage. To estimate moderate to high Chl content and vegetation cover, using the "green" channel instead of the "red" one in a vegetation index was suggested (Yoder and Waring, 1994; Gitelson et al., 1996). A green atmospherically resistant vegetation index (GARI), tailored on the concept of ARVI (Atmospherically Resistant Vegetation index—Kaufman and Tanré, 1992) was developed and is expected to be as resistant to atmospheric effects as ARVI but more sensitive to a wide range of Chl content.

The sensitivity of the spectral reflectance to Chl content varies widely in visible range of the spectrum (Gitelson and Merzlyak, 1996). That is why any variation in the spectral location of a given channel might change the NDVI value. Climate change research requires long time sequences in order to observe the effect of atmospheric composition, climate and soil nutrients on vegetation (Myneni et al., 1997a; Braswell et al., 1997). The aim of the article is to study the spectral properties of the MODIS NDVI and its difference from the NDVI-AVHRR.

In this article we suggest an optimization of the MODIS observations to fit the AVHRR time series of vegetation indexes, by avoiding a step in the NDVI in switching between the satellites, and avoiding a change in the sensitivity to Chl of these two instruments. We use bit full canopy and leaf spectra in the optimization. A MODIS oriented vegetation index with maximum sensitivity to Chl is also discussed.

METHODS

Plants

Plant leaves were collected in different geographical and climatic zones (in Israel, Germany, Russia, and the United States). The data sets covered all stages of leaf development and senescence. The leaves of a beech tree (*Fagus sylvatica* L.), an elm tree (*Ulmus minor* Miller), and a wild wine shrub (*Parthenocissus tricuspidata*) growing on the campus of the University of Karlsruhe (Germany) were taken in August and September 1996. Three sets of beech leaves (28 leaves altogether), two sets of wild vine leaves (16 leaves), and a set of elm leaves (nine leaves) were measured (Gitelson et al., 1998). Eight to ten week old tobacco plants (*Nicotiana tabacum* L.) were cultivated on a mineral-containing peat in the greenhouse in the Botanical Garden of the University of Karlsruhe under standard conditions (Lichtenthaler et al., 1996).

Norway maple (*Acer platanoides* L.) and horse chestnut (*Aesculus hippocastanum* L.) leaves were collected in the Botanical Garden of the Moscow State University (Russia) during 1991–1995 from spring to late autumn (Gitelson and Merzlyak, 1994a; 1996). Cotoneaster leaves were collected during autumn 1995.

The leaves of fig (*Ficus carica* L.), oleander (*Nerium oleander* L.), hibiscus (*Hibiscus esculentum* L.), vine (*Vitis vinifera* L.), and rose (*Rosa rugosa* Thunb) plants were collected during winter 1995/96 in the Sede-Boker Campus, Ben-Gurion University of the Negev (Israel).

Reed canopies were cultivated in Mead farm belonging to University of Nebraska-Lincoln (USA) and measured in June 1996. Nineteen plots were chosen with very different color from yellowish-green to green.

Reflectance and Transmittance Spectra

Reflectance and transmittance spectra of a beech, an elm, a wild wine, and tobacco leaves were measured in the spectral range between 400 nm and 800 nm with a spectral resolution of 1 nm using a spectrometer with integrating sphere UV-2101 PC, Shimadzu (Lichtenthaler et al., 1996; Gitelson et al., 1998).

Reflectance and transmittance spectra of maple, chestnut, and cotoneaster leaves were measured in the range 400–800 nm, with a spectral resolution of 2 nm with a Hitachi 150-20 spectrophotometer equipped with an integrating sphere (Gitelson and Merzlyak, 1994a,b).

An LI-1800 radiometer with an integrating sphere was used to measure reflectance and transmittance spectra of fig, oleander, hibiscus, vine, and rose leaves in the range 350–1100 nm, with a spectral resolution of 2 nm.

Upwelling radiance of reed canopy, L_{up}, was measured in the range 400–850 nm by Ocean Optics ST1000 spectroradiometer. In order to estimate the solar downwelling signal, L_0, Lambertian Spectrolon panel was used. Light was brought to the instrument using fiber optic cables with an effective field of view of about 25°. L_{up} was measured at least six times at about 6 m above the reed, and means of these measurements were used. Each observed upwelling radiance spectrum of the canopy was divided by the appropriate upwelling radiance spectrum of the reference plate to give a reflectance as $R = L_{up}/L_0$.

While the leaf spectra and the reed canopy spectra are used for the optimization of the MODIS NDVI data series, an independent data set acquired in May 1996 in Israel is used to evaluate the optimization. Upwelling radiance of various surfaces—from bare soil to very dense vegetation—was measured from light aircraft (altitude at about 500 m) in spectral range 350–2500 nm by Field Spec spectroradiometer (Analytical Spectral Devices Inc.) with 25° FOV. Vegetation cover varied from 0% to 100%.

Leaf Pigments Determination

The leaf pigments were determined quantitatively at the same spot of the leaf where the transmittance and reflectance spectra had been taken. Circular pieces of 10-mm diameter were cut from the leaves and extracted with

Table 1. Pigment Content for Leaves and Canopy Studied[a]

Leaves	n	Chl-a+b Min	Chl-a+b Max	Chl-a Min	Chl-a Max	Car Min	Car Max	Chl-a+b/Car Min	Chl-a+b/Car Max
Elm	9	63	638	43	475	27	133	2.3	4.8
Beech	28	85	675	63	541	30	137	1.3	6.7
Tobacco	13	83	411	70	308	32	82	2.6	5.84
Chestnut	25	6.8	630	5	462	29	250	1.86	6.32
Wild wine	16	41	472	30	349	12	103	2.5	4.8
Fig	11	115	568	100	451	12	120	2.4	4.9
Oleander	7	154	479	123	350	14	98	2.45	5.2
Hibiscus	10	89	598	72	448	18	127	2.13	6.1
Rose	9	96	651	84	501	27	105	2.6	5.9
Maple	40	2.8	535	1.7	397	29	165	0.057	5.31
Cotoneatser	7	2.9	449	2	335	62	154	0.034	2.91
Reed canopy	19	108	513	80	473	18	144	2.4	5.10

[a] *n* is number of samples, Chl-*a*+*b*, Chl-*a*, and Car are contents of total chlorophyll, chlorophyll *a*, and carotenoids, respectively in mg/m^2; Chl-*a*+*b*/Car is ratio of total chlorophyll to carotenoid contents.

100% acetone using a mortar. The content of chlorophyll *a* and *b* as well as of total carotenoids was determined spectrophotometrically and calculated using the equations of Lichtenthaler (1987).

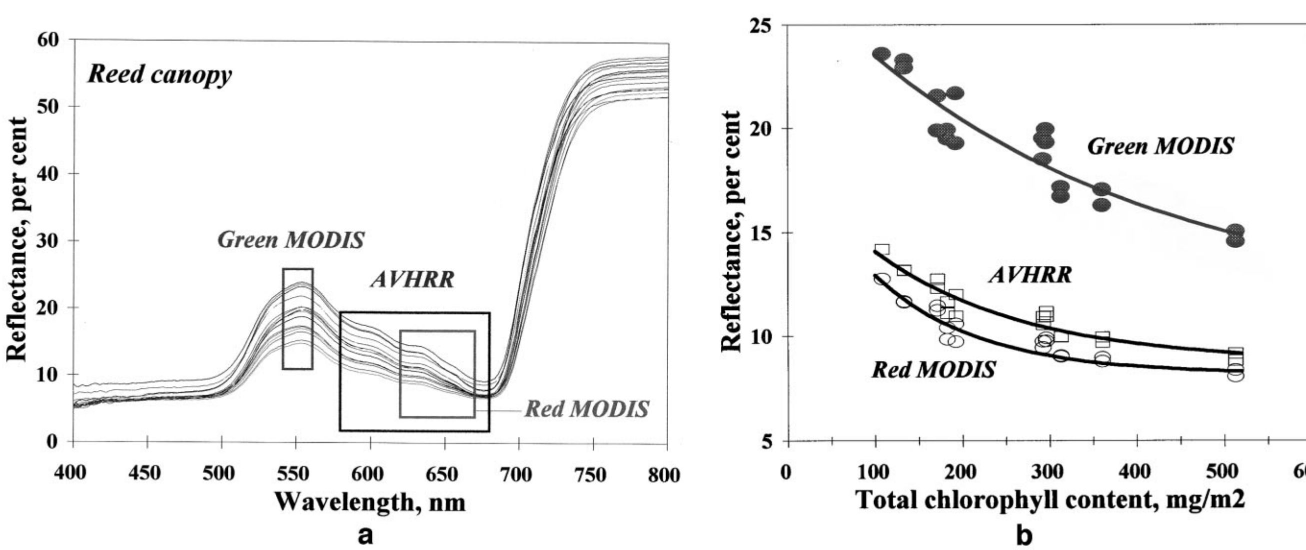
The color of leaves in stage of development was from white-green to dark-green, while in the stage of senescence it varied from dark-green to completely yellow. Among leaves studied pigment contents and composition varied in a very wide range (Table 1).

At least five samples were taken for each spot of reed canopy, and pigment contents were determined for each of them. Then, average Chl content was calculated and used as a characteristic of each plot.

RESULTS AND DISCUSSION

The need to optimize the MODIS NDVI to fit the AVHRR data series is demonstrated in Figure 1. Reflectance spectra of reed canopies for a wide range of chlorophyll concentrations are shown in Figure 1a. The lower

Figure 1. a) Reflectance spectra of reed canopy. The bottom spectrum corresponds to maximal Chl content (513 mg/m^2) and the top one to minimal Chl content (108 mg/m^2). The spectral positions of MODIS green and red channels and AVHRR red channel are shown. The differences in the spectral properties and sensitivity to chlorophyll content between these bands can be seen. b) Integrated reflectance of reed canopy in the AVHRR and MODIS bands plotted vs. Chl content. Average values of reflectance in the narrower MODIS red channel are considerably lower than that in the AVHRR red channel. As a result, the MODIS red channel loses its sensitivity to chlorophyll content for fully vegetated surface, and is less sensitive than the AVHRR. In the range of Chl variation from 100 mg/m^2 to 500 mg/m^2, standard deviation of reflectance in AVHRR red band was at least 20% higher than that of red MODIS band.



spectrum corresponds to maximal Chl content (513 mg/m^2) and the uppermost one corresponds to minimal Chl content (108 mg/m^2). The location of the narrower MODIS red and green bands and of the broader AVHRR red band are indicated. The AVHRR and MODIS Integrated reflectance in these bands are plotted versus Chl content in Figure 1b. The differences in the vegetation spectral properties and sensitivity to chlorophyll content between these bands can be seen.

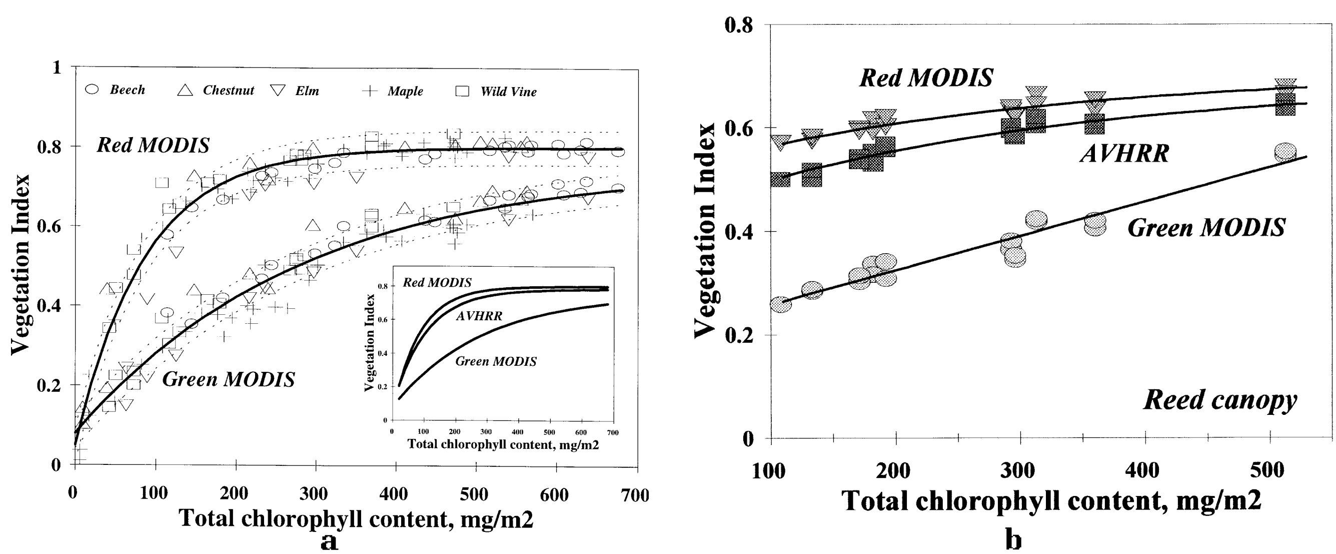
The spectral reflectance of reed canopy and other plants are characterized by:

- a minimum sensitivity to Chl content in the range 400–500 nm and in the near-infrared (NIR) range of the spectrum;
- low sensitivity to Chl content near 670 nm (the "red" absorption band of Chl-*a*) for white-green to dark-green vegetation, and high sensitivity to small Chl content (up to 150 mg/m^2);
- a high sensitivity to Chl variation in a wide range from 530 to 630 nm and also near 700 m.

For all types of vegetation studied, reflectance near 670 nm decreases sharply when Chl content changes from 0 to about 100 mg/m^2 (white-green or yellow-green vegetation color) and it is almost insensitive to Chl variation for Chl >150 mg/m^2 when vegetation color changes from slightly green to dark-green (not shown). Reflectance in the spectral range 530–630 nm, and near 700 nm, were nearly equally sensitive to Chl content from 2 mg/m^2 to more than 600 mg/m^2. For yellow-green to green reed canopy (Fig. 1) with Chl content >100 mg/m^2, standard deviation of reflectance at 550 nm and 700 nm was four times higher than that at 670 nm.

The sensitivity of reflectance to Chl content varies widely in spectral range from 550 nm to 670 nm (Fig. 1). This range includes portion of spectrum from 550 nm to 630 nm with high variation of reflectance, when Chl content varies from low to high values, as well as range near 670 nm, where sensitivity to Chl content is high for low Chl and very low for moderate to high Chl values. The AVHRR red band (Band 1) is quite wide; it includes portions of spectrum with both high (shorter wavelengths) and low (longer wavelengths) reflectance variation. The red MODIS band is narrower than the AVHRR red band (see Fig. 1b), has a lower spectral variation of reflectance and lower average reflectance for each Chl content. As a result, in the range of Chl variation from 100 mg/m^2 to 500 mg/m^2 standard deviation of reflectance in AVHRR red band was found to be at least 20% higher than that of red MODIS band.

Figure 2. a) MODIS green and red vegetation indexes plotted vs. total chlorophyll content for five studied species of leaves. Indexes were calculated as $(\rho_{NIR}-\rho_x)/(\rho_{NIR}+\rho_x)$, where ρ_{NIR} is reflectance at 841–876 nm. For MODIS green index, ρ_x is the reflectance in the range 545–565 nm. For MODIS red index, ρ_x is in the range 620–670 nm. Best fit functions for each index are presented. Standard deviation of functions showed by dotted lines were less than 0.04. Very different relations of red and green indexes with Chl content can be seen: red index leveled for low Chl content (100–150 mg/m^2, i.e., for white-green leaves) while green index remains sensitive to Chl content in a wide range of its variation from pale practically "chlorophyll-free" to dark-green leaves. *Inset:* Best fit functions "vegetation indexes vs. Chl content" for leaves of 12 studied species. For NDVI-AVHRR ρ_x is the reflectance in the range 580–680 nm and NIR is reflectance in the range 725–1100 nm. Note the difference between AVHRR and red MODIS indexes. b) MODIS green and red vegetation indexes plotted versus total chlorophyll content for reed canopy. Indexes were calculated as in Figure 2a. Best fit functions for each index are presented. Coefficients of variation of the indexes (ratio of standard deviation of index to average index value) in the range of Chl variation from 100 mg/m^2 to more than 500 mg/m^2 were 5.3% for red, 8% for AVHRR, and 23.4% for green index. Note that the AVHRR NDVI value was considerably lower than that of the MODIS red NDVI index.



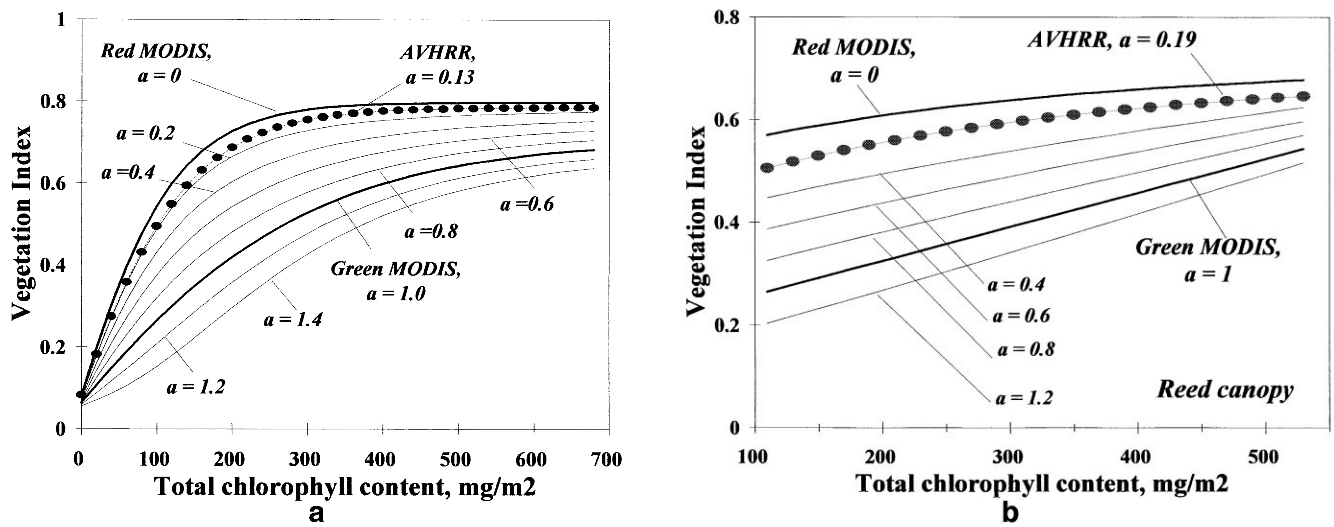


Figure 3. a) Vegetation indexes calculated as a function of $VI=\{\rho_{NIR}-[\mathbf{a}\rho_{green}+(1-\mathbf{a})\rho_{red}]\}/\{\rho_{NIR}+[\mathbf{a}\rho_{green}+(1-\mathbf{a})\rho_{red}]\}$ plotted versus Chl content for various **a** values. Green and red MODIS indexes are best fit functions for leaves of 12 species studied (Fig. 2a). The NDVI-AVHRR index can be calculated for leaves using radiance in green, and red, MODIS channels with $\mathbf{a}=0.13$. Therefore, based on these leaf spectra, a MODIS vegetation index with $\mathbf{a}=0.13$ can provide the best continuation for the NDVI-AVHRR data series, both in absolute value and in sensitivity to the chlorophyll content. b) Vegetation indexes for reed canopies plotted versus Chl content for various values of **a**. Indexes were calculated as in Figure 3a with green and red MODIS vegetation indexes that are best fit functions for reed canopies (solid lines in Fig. 2a). NDVI-AVHRR can be calculated for reed canopies using radiance in green and red MODIS channels, with $\mathbf{a}=0.188$. Therefore, based on these canopy spectra, a MODIS vegetation index with $\mathbf{a}=0.18$ can provide the best continuation for the NDVI-AVHRR data series. The canopy and leaf spectra evaluation of **a** gives a preliminary indication of the best method to provide continuation of the NDVI-AVHRR data series. The actual value of **a** should be found using a larger data set.

These differences in spectral behavior of reflectance in visible range of the spectrum manifest itself in the relationship between vegetation index and Chl content for the leaves studied here (Fig. 2a). Vegetation indexes (VIs) were computed from the spectral data for red and green MODIS channels (VI_{RED} from 620 nm to 670 nm, VI_{GREEN} from 545 nm to 565 nm), and for NDVI-AVHRR. Very different relations of red and green MODIS indexes with Chl content can be seen: VI_{RED} levels for low Chl content (100–150 mg/m^2, i.e., for white-green leaves) while VI_{GREEN} remains sensitive to Chl content in a wide range of its variation from pale practically "chlorophyll-free" to dark-green leaves. The inset in Figure 2a presents best fit functions for the vegetation index vs. Chl content for 12 species of leaves:

$$VI_{RED}=0.75\ \exp(-Chl/86.8)+0.05, \qquad (1)$$

with root-mean square deviation equal to 0.042 and determination coefficient $r^2=0.93$;

$$VI_{GREEN}=0.6\ \exp(-Chl/286)+0.08, \qquad (2)$$

with root-mean square deviation equal to 0.036 and determination coefficient $r^2=0.95$;

$$\text{NDVI-AVHRR}=0.7\ \exp(-Chl/107)+0.09, \qquad (3)$$

with root-mean square deviation equal to 0.039 and determination coefficient $r^2=0.94$.

Though red spectral channels of MODIS and AVHRR do not diverge considerably, the difference in value and behavior of NDVI-AVHRR and VI_{RED} is significant: $\Delta NDVI \sim -0.05$ [compare Eqs. (1) and (3)]. The common feature of both indexes is that NDVI-AVHRR and VI_{RED} saturate for moderate to high Chl content.

A similar dependence of the vegetation index on Chl takes place for reed canopies (Fig. 2b). Minimal Chl content was about 100 mg/m^2 (yellowish-green color), and the functions were roughly linear. Coefficients of variation (ratio of standard deviation of index to average index value) in the range of Chl from 100 mg/m^2 to more than 500 mg/m^2 were 5.3% for VI_{RED}, 8% for NDVI-AVHRR, and 23.4% for VI_{GREEN}. NDVI-AVHRR value was considerably lower than that of red MODIS index.

Thus, NDVI-AVHRR and VI_{RED} differ significantly enough so that a continuation of the AVHRR data series will not be possible by using the narrower MODIS red channel. In order to derive from MODIS data that are more similar to the AVHRR data, for continuation of the AVHRR data series, we suggest using a weighted average of the MODIS red and green channels.

The weighted channel selection is done by studying the dependence of the vegetation index vs. Chl to different proportions of green (ρ_{green}) and red (ρ_{red}) MODIS channels in Eq. (4):

$$VI=\{\rho_{NIR}-[\mathbf{a}\rho_{green}+(1-\mathbf{a})\rho_{red}]\}/\{\rho_{NIR}+[\mathbf{a}\rho_{green}+(1-\mathbf{a})\rho_{red}]\}. \qquad (4)$$

The variation in the coefficient **a** reflects the contribu-

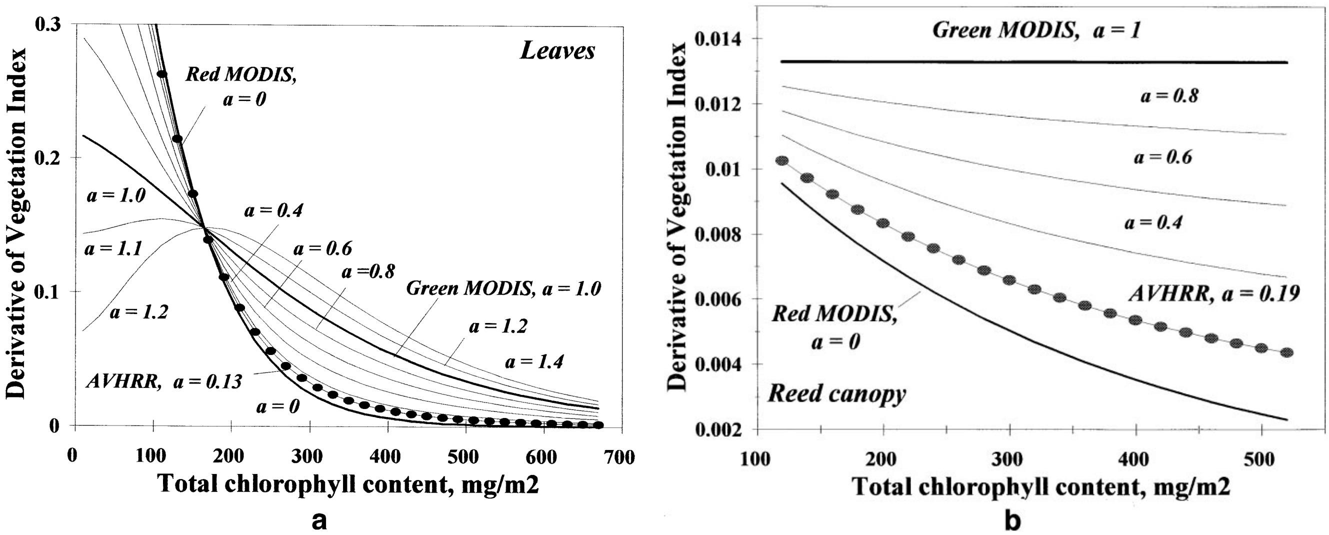


Figure 4. a) The first derivative of leaves vegetation indexes (Fig. 3a) plotted vs. Chl content for several values of the coefficient **a**. Red MODIS index (**a**=0) had a maximal sensitivity to low Chl content, decreasing sharply with increase in Chl. For moderate to high Chl content, the sensitivity of indexes with **a**=1–1.4 was the highest. b) The first derivative of vegetation indexes for reed canopy (Fig. 3b) plotted vs. Chl content for different coefficients **a**. Red MODIS index had smaller sensitivity to Chl content, ranged from 100 mg/m^2 to more than 500 mg/m^2, than that of the green MODIS index. Sensitivity of NDVI-AVHRR to Chl content was found to be considerably higher than that of the MODIS red index.

tion of green MODIS channel to VI: **a**=0 corresponds to VI_{RED} and **a**=1 corresponds to VI_{GREEN}. Thus, we have found that, for the present leaf spectra, NDVI-AVHRR can be calculated using radiance in green and red MODIS channels, ρ_{green} and ρ_{red} with **a**=0.13.

Figure 3 demonstrates the variation in shape of the curves "VI vs. Chl content" for different values of the coefficient **a**. When Chl content is less than 150 mg/m^2, VI_{RED} (**a**=0) is very sensitive to Chl content. For low Chl content, addition of the radiance of the green channel (increase in coefficient **a**) decreases VI sensitivity to Chl; the reason is that for low Chl content VI_{GREEN} is three times less sensitive to Chl variation than that of VI_{RED}.

The picture changes drastically for Chl more than 200 mg/m^2 (white-green to green vegetation). For Chl >200 mg/m^2, VI_{RED} saturates (Fig. 3a), thus, the first derivative of VI, that is, the sensitivity to Chl, drops sharply (Fig. 4a) reaching almost zero values for green vegetation (Chl >300 mg/m^2). Addition of the green channel increases the sensitivity of VI to high Chl content. For Chl >300 mg/m^2 the sensitivity of VI with **a**=1–1.4 at least six times higher than that of VI_{RED} (**a**=0).

A similar behavior of function "VI vs. Chl content" was found for reed canopies with Chl >100 mg/m^2 (Fig. 3b). In the studied range of Chl content, VI_{RED} has the lowest sensitivity to Chl (Fig. 4b) and the sensitivity increases with addition of green channel radiance (increase in coefficient **a**), reaching maximal values for VI_{GREEN} (**a**=1). For this data set, AVHRR-NDVI can be represented by mixing 81% of the MODIS red channel with 19% of the green channel. Therefore, AVHRR-NDVI fits well to the weighted average between the MODIS red and green channels with weighting factors **a** differ from 0.13 (for 12 types of leaves studied) and 0.19 (for reed canopy).

Independent data sets were used to test optimization of the MODIS NDVI to the AVHRR data series by using a mixture of the 85% red and 15% green channels. The difference between red MODIS and AVHRR vegetation indices was calculated and plotted versus AVHRR-NDVI (Figs. 5a and b). For the data plotted in Figure 5a, maximal difference in MODIS and AVHRR indices reached 0.04, whereas for the data presented in Figure 5b it was smaller (<0.025). In the same figures, the difference between weighted average of the MODIS red and green channels with **a**=0.15 and the AVHRR is presented (it is named "optimized MODIS"). It can be seen that mixing 85% of the MODIS red channel with the 15% of the green channel, the difference between optimized MODIS and AVHRR indexes drop drastically. That correction allows decreasing root-mean square variation from 0.040 to 0.004 for the data presented in Figure 5a, and from 0.022 to 0.0016 for the data in Figure 5b.

The sensitivity of the vegetation indexes based on the green and red channels to the Chl content is very different. For estimation of low Chl content in vegetation, VI_{RED} (VI with coefficient **a** near zero) is the best index, while for estimation of moderate to high Chl content, **a** should be near 1 (VI for **a**=1). To estimate Chl content per unit area in a wide range of its variation, different indexes are required. For low Chl content per

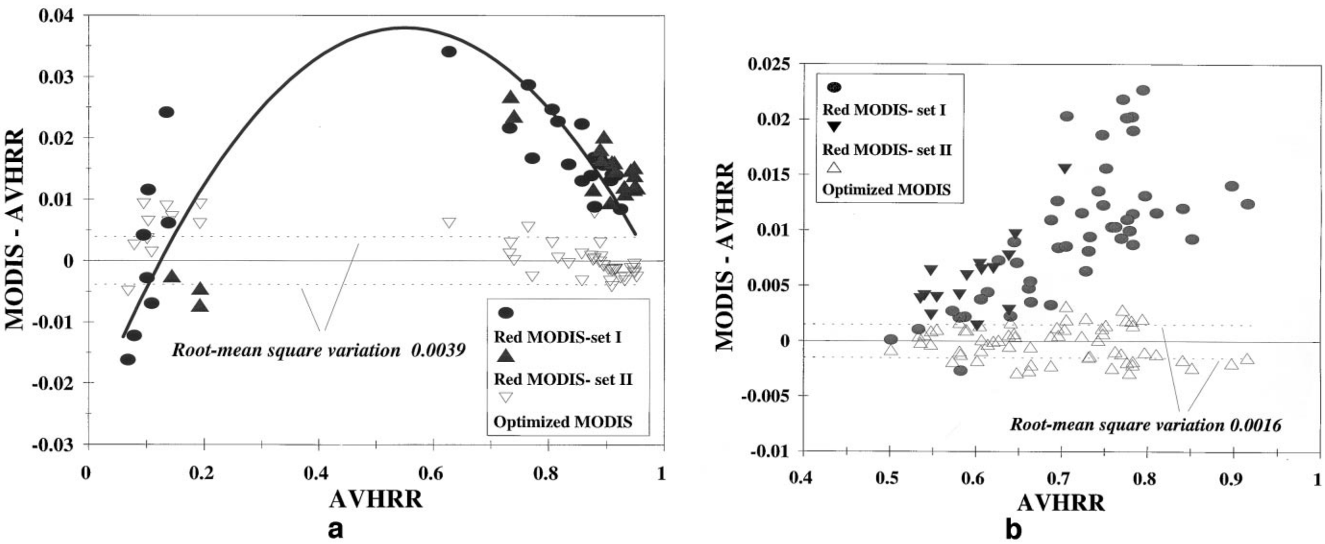


Figure 5. The difference between red MODIS and AVHRR vegetation indices plotted vs. AVHRR-NDVI for four independent data sets measured from aircraft. The difference between the optimized MODIS, given by the weighted average of 85% of MODIS red channel and 15% of the green channel, and the AVHRR is also plotted. The optimization allows the difference between MODIS and AVHRR indexes to decrease by tenfold [from 0.04 to 0.004 (a) and from 0.022 to 0.0016 (b)].

unit area (<100 mg/m^2), the red MODIS VI (**a**=0) is the most suitable index. When Chl content is higher 150 mg/m^2, index with more "contribution" of green channel is required. For moderate to high Chl content, the index with coefficient **a** close to 1 is the most suitable. For dense vegetation (forest, green grass, crop, and so on) green MODIS VI (**a**=1) and even VI with **a**>1 is more sensitive to the state of vegetation. This is in accord with Verstraete and Pinty (1996), who suggest that optimal indexes should be designed for specific applications and particular instruments.

We may try and combine the high sensitivity of the VI for low Chl using the red channel and to high Chl using the green channel by applying a transition from red to green VI as a function of the Chl content, thus expressing the Chl content by

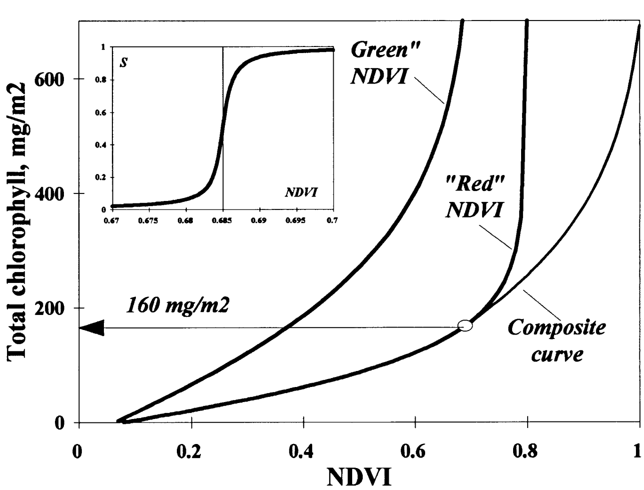
$$\mathrm{Chl}=S*\mathrm{VI}_{\mathbf{a}=1}+(1-S)*\mathrm{VI}_{\mathbf{a}=0}, \tag{5}$$

where

$$S=1/\arctan[1000(\mathrm{VI}-0.685)+0.5] \tag{6}$$

Figure 6 shows the function "Chl vs. VI" for the measured leaves; Eqs. (1) and (2) (Fig. 2a) were used to calculate $\mathrm{VI}_{\mathbf{a=0}}$ (i.e., $\mathrm{VI}_{\mathrm{RED}}$) and $\mathrm{VI}_{\mathbf{a=1}}$ (i.e., $\mathrm{VI}_{\mathrm{GREEN}}$). In insert the function S is shown. The S-function is very small for VI<0.6 and then increases sharply reaching values of about 1 for higher VI. Thus, the composite curve almost coincides with function $\mathrm{VI}_{\mathrm{RED}}$ for low Chl and with $\mathrm{VI}_{\mathrm{GREEN}}$ for moderate to high Chl content. To use such approach, investigation of function "VI vs. Chl content" for different kinds of canopies is required. This function likely will be different from that for leaves (Fig. 5) and Eqs. 5 and 6 should be considered as an example of a combined vegetation index.

Figure 6. Total Chl content in studied leaves vs. value of vegetation index. Composite curve was calculated by Eq. (5). S-function [Eq. (6)] is shown in insert. The composite curve coincides with red vegetation index for low Chl content (white-green leaf color), and with green index for moderate to high Chl content. Thus, the suggested vegetation index is almost equally sensitive to Chl content in a wide range of its variation.



CONCLUSIONS

MODIS is a much more accurate and versatile instrument to monitor the global vegetation dynamics then the AVHRR, but the difference between its spectral properties and those of the AVHRR do not allow a direct combination of the AVHRR and MODIS data series into one continued sequence for monitoring global vegetation. Studies of the interaction between atmospheric composition, climate, and vegetation require highly accurate and long data series. We showed that using weighted average between the MODIS red and green channels, we can fit the AVHRR vegetation index very well, although the weighting factors differ slightly from leaves to canopy. Approximately, AVHRR-NDVI can be represented by mixing 85% of the MODIS red channel with 15% of the green channel. The present analysis should be considered as an example of the approach and the specific values of the coefficient **a**, which combines the red and green channel for a smoothly matched data series, should be derived from a much larger data base of canopy spectra, and eventually using the MODIS and AVHRR data series.

We also show that the different sensitivity of the vegetation index based on the green or red channels to the chlorophyll content can be combined for a better monitoring of the vegetation dynamics. A smooth weighting function that selects the red VI for low chlorophyll and green VI for high chlorophyll can be used to optimize monitoring of vegetation cover and chlorophyll content in one index. This application also requires a large representative data set of canopy spectra to derive the right optimization of the approach.

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