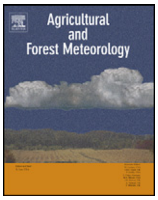
Agricultural and Forest Meteorology xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Short communication

Advantages of a two band EVI calculated from solar and photosynthetically active radiation fluxes

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ARTICLE INFO

Article history:
Received 23 January 2009
Received in revised form 20 March 2009
Accepted 26 March 2009

Keywords:
Burn severity
Vegetation phenology
NDVI
EVI2
Tundra

ABSTRACT

A two band Enhanced Vegetation Index (EVI2) without the blue band reflectance has recently been developed as a proxy for the phenology, quantity, and activity of vegetation. We compared the ability of EVI2 and the more commonly used Normalized Difference Vegetation Index (NDVI) to resolve differences in surface greenness and Leaf Area Index (LAI) among three sites located along a burn severity gradient in arctic tundra. We calculated vegetation indices from solar and photosynthetically active radiation fluxes, and validated these calculations against vegetation indices from the Terra MODerate resolution Imaging Spectroradiometer (MODIS) and ground-based spectroradiometer measurements. EVI2 performed slightly better than NDVI when comparing tower derived vegetation indices to MODIS and spectroradiometer derived vegetation indices. Burn severity decreased albedo and resulted in differences in soil background reflectance among sites. Soil darkening had no effect on EVI2, but artificially increased NDVI, resulting in separate relationships between NDVI and Leaf Area Index for burned and unburned tundra. Our results indicate that EVI2 has several advantages over NDVI including the ability to resolve LAI differences for vegetation with different background soil reflectance.

1. Introduction

The Normalized Difference Vegetation Index (NDVI) is commonly used to monitor the phenology, quantity, and activity of vegetation. NDVI can be measured remotely with satellites, calculated from ground-based measurements of surface reflectance, or calculated from measurements of incident and reflected solar and Photosynthetically Active Radiation (PAR) (Huete et al., 1994; Wilson and Meyers, 2007). Although NDVI provides researchers with a way to monitor vegetation, the sensitivity of NDVI to background reflectance and the tendency of NDVI to saturate at high leaf area may limit the use of this technique across a variety of vegetation types (Huete, 1988; Huete et al., 2002). The Enhanced Vegetation Index (EVI) is often employed as an alternative to NDVI because it is less sensitive to these limitations, but requires information on reflectance in the blue wavelengths, which is not available on some satellites and is difficult to extract from broadband radiation measurements. A two band EVI (EVI2) that does not require the blue band reflectance has been developed by taking advantage of the autocorrelative properties of surface reflectance spectra between the red and blue wavelengths (Jiang et al., 2008). However, the sensitivity of this autocorrelation to changes in background reflectance is not fully understood, and further testing is required before a universal relationship between reflectance in the red and blue wavelengths is established.

We used leaf area harvests and three independent measures of surface reflectance from three sites located along a burn severity gradient (i.e. severe, moderate, unburned) to determine the sensitivity of NDVI and EVI2 to changes in background reflectance. Burn severity influenced background reflectance through differences in the amount of vegetation consumed in the fire, which in turn, resulted in albedo differences along the burn severity gradient. NDVI and EVI2 derived from incident and reflected solar and PAR measurements were validated against NDVI, EVI, and EVI2 derived from the MODerate resolution Imaging Spectrodiometer (MODIS) satellite and ground-based spectroradiometer measurements. The seasonal pattern and differences in magnitude of EVI and NDVI among the severe, moderate, and unburned sites were compared to determine the ability of the vegetation indices to resolve differences in surface greenness among sites. The ability of NDVI and EVI2 to capture differences in leaf area across the burn severity gradient was assessed with small plot based measurements of surface reflectance and Leaf Area Index (LAI) across burned and unburned tundra sites.

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doi:10.1016/j.agrformet.2009.03.016

Please cite this article in press as: Rocha, A.V., Shaver, G.R., Advantages of a two band EVI calculated from solar and photosynthetically active radiation fluxes. Agric. Forest Meteorol. (2009), doi:10.1016/j.agrformet.2009.03.016

2. Methods

2.1. Site descriptions

We established three sites along a burn severity gradient in late May 2008 in the southern area of the Anaktuvuk River fire scar on the north slope of Alaska. The Anaktuvuk River fire burned a 1000 km^2 area during the late 2007 growing season and created a mosaic of patches that differed in burn severity. The severely burned site (68.99°N, 150.28°W) consisted of a large (>1 km^2) area in which all of the green vegetation was consumed in the fire and some of the organic matter had burnt to the mineral soil in many places. The moderately burned site (68.95°N, 150.21°W) consisted of a large area with smaller (~1–10 m^2) patches of completely and partially burned tundra intermixed across the landscape. The unburned site (68.93°N, 150.27°W) was located in a large area of tundra that was unaffected by the fire, and was composed of vegetation that was typical of tussock tundra.

2.2. Instrumentation and available data

Reflected radiation was measured with satellite based, tower based, and hand-held sensors, which operated at different temporal, spatial, and spectral resolutions. The Terra MODIS satellite measured surface reflectance at seven different spectral bands at a spatial scale of 0.25 km^2. We used the eight-day maximum composite MODIS product (MOD09A1) and extracted vegetation indices from a 1.0 km^2 area centered around each tower site (http://modis.gsfc.nasa.gov/). MODIS images were reprojected to geographic lat/long in ENVI (ITT Visual Information Solutions, Boulder, CO), and images with clouds obscuring areas of interest were not used in the analysis. Reflected and incident solar radiation was measured every half hour with a pyranometer (CNR-1; Kipp and Zonen), and reflected and incident PAR was measured every half hour with a quantum sensor (LI-190SA; Li-Cor, Lincoln, NB). Downward looking radiation instruments had a 250 m radial field of view of the ground (Schmid, 1997; Wilson and Meyers, 2007) and were situated at a height of ~2.5 m on a stainless steel tripod. Ground-based reflectance measurements were made at each site every two to three weeks with a hand-held Unispec-DC spectroradiometer (PP-systems, Haverhill, MA, USA). The Unispec had a 20 cm radial field of view of the ground and measured surface reflectance at a spectral resolution of 2.0 nm from 380 to 1050 nm. A total of 80 Unispec measurements were conducted in eight compass directions around the tripod where radiation measurements were occurring, and averaged at each site for each sampling period.

2.3. Calculation of vegetation indices

NDVI and EVI2 were calculated from reflectance in the Near InfraRed (ρ_{NIR}: 841–876 nm) and red (ρ_{RED}: 620–670 nm) wavelengths, whereas EVI incorporated reflectance in the NIR, red and blue (ρ_{BLUE}: 459–479 nm) wavelengths (Huete et al., 1994; Jiang et al., 2008) [Eqs. (1)–(3)].

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{RED}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{RED}}} \tag{1}$$

$$\mathrm{EVI} = 2.5\frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{RED}}}{\rho_{\mathrm{NIR}} + 6\rho_{\mathrm{RED}} - 7.5\rho_{\mathrm{BLUE}} + 1} \tag{2}$$

$$\mathrm{EVI2} = 2.5\frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{RED}}}{\rho_{\mathrm{NIR}} + 2.4\rho_{\mathrm{RED}} + 1} \tag{3}$$

We compared NDVI, EVI, and EVI2 calculated from MODIS and ground-based Unispec surface reflectance to NDVI and EVI2 calculated from solar and photosynthetically active radiation measurements. MODIS derived NDVI [Eq. (1)] and EVI2 [Eq. (3)] were calculated using Band 1 for ρ_{RED} and Band 2 for ρ_{NIR}, whereas MODIS derived EVI was calculated using Eq. (2) and Band 3 for ρ_{BLUE}. Ground-based spectral reflectance measurements were converted to NDVI, EVI, and EVI2 using Eqs. (1)–(3) by averaging surface reflectance at the corresponding wavelengths for ρ_{NIR}, ρ_{RED}, and ρ_{BLUE}. Incoming (i) and reflected (r), solar (S) and PAR measurements were converted to ρ_{NIR} and ρ_{RED} using the approach derived by Wilson and Meyers (2007) [Eqs. (4) and (5)].

$$\rho_{\mathrm{RED}} = \frac{\mathrm{PAR_r}}{\mathrm{PAR_i}} \tag{4}$$

$$\rho_{\mathrm{NIR}} = \frac{S_{\mathrm{r}} - 0.45(S_{\mathrm{i}}\rho_{\mathrm{RED}})}{0.55S_{\mathrm{i}}} \tag{5}$$

NDVI and EVI2 derived from radiation measurements (i.e. "tower derived") were then calculated using Eqs. (1) and (3). Surface albedo was calculated as $S_{\mathrm{r}}/S_{\mathrm{i}}$. Solar zenith effects on vegetation indices were removed from the time series by filtering out non-midday values (Wilson and Meyers, 2007). Extremely cloudy conditions and snow accumulation on the sensors affected the calculation of vegetation indices by changing the ratio between incoming PAR and S ($\mathrm{PAR_i}/S_{\mathrm{i}}$), and were filtered out by removing ratios that were less than 2.0 and greater than 2.2. The remaining data were used to compute daily averages and 95% confidence intervals for each vegetation index, and later smoothed with a 5-day moving average. Linear least squares regression and the Root Square Mean Error (RSME) were computed to test the correspondence between MODIS and spectroradiometer derived NDVI, EVI, and EVI2 to NDVI and EVI2 derived from tower measurements.

2.4. Surface greenness and leaf area index (LAI)

Leaf area harvests and surface spectroradiometer measurements (ASD Fieldspec3 Spectroradiometer; ASD Inc., Boulder, CO) were conducted for a 0.10 m^2 area in 22 plots along a 66 m transect in late July of 2008 at the severely burned site. Harvested leaves were taken back to the lab and sorted by species. A subset of plots was scanned on a leaf area meter (LI-3050C Transparent Belt Conveyer; LI-COR, Lincoln, NB), and all leaf material for each plot was dried in an oven for 2 days at 60 °C and weighed. Specific leaf areas for each plant species were calculated and then used to calculate LAI for the remaining plots. NDVI and EVI2 for each plot were calculated from the spectroradiometer measurements using Eqs. (1) and (3). NDVI, EVI2, and LAI data from the severely burned site were then compared with a larger data set from unburned tundra at a variety of arctic sites, which were processed in a similar fashion (Shaver et al., 2007). Because LAIs at the burned site were lower on average than reported in the Shaver dataset, we filtered the data for LAIs that were greater than 2.0, so that the saturation of NDVI at high leaf area would not affect comparisons between burned and unburned sites. Linear regression was used to test the relationship between surface greenness (i.e. NDVI and EVI2) and LAI, while ANalysis of COVAriance (ANCOVA) was used to determine if the slopes of the EVI2, NDVI and LAI relationships differed for burned and unburned tundra.

3. Results

3.1. Seasonal patterns of albedo and surface greenness across the burn severity gradient

The seasonal pattern and the magnitude of albedo differed across the burn severity gradient (Fig. 1A). Seasonal changes in albedo at the unburned site were small, whereas seasonal changes

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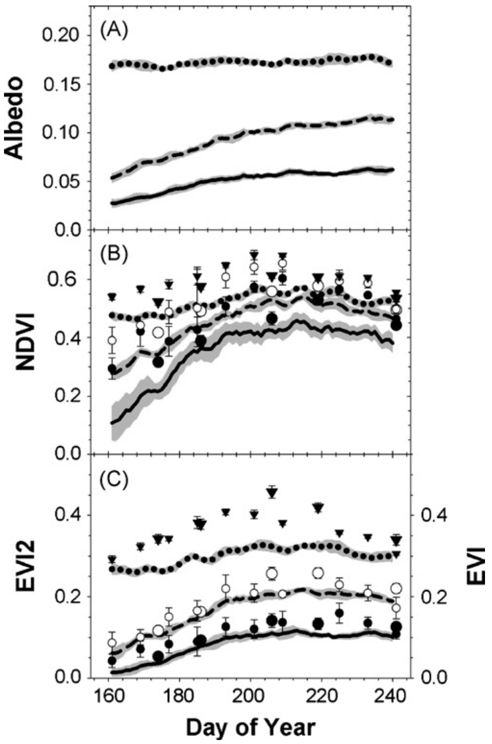

Fig. 1. Seasonal course of albedo (A), NDVI (B), and EVI2/EVI (C) at the severe (solid line/closed circles), moderate (hatched line/open circles) and unburned (dotted line/triangles) sites. Lines represent vegetation indices derived from radiation tower measurements and symbols represent vegetation indices derived from MODIS (small symbols) and Unispec (large symbols) data. Gray area enveloping lines and error bars on symbols represent 95% confidence intervals. EVI2 (left axis) derived from radiation measurements is compared to EVI (right axis) derived from MODIS and Unispec data in panel C.

in albedo at the burned sites were large, especially in the beginning of the growing season (DOY: 160–190), and indicated vegetation recovery at these sites. The burn decreased average growing season albedo by 46% at the moderately burned site and by 71% at the severely burned site, as compared to the unburned site.

Differences in the magnitude and seasonal patterns of NDVI among sites were also observed for MODIS, Unispec, and radiation measurements (Fig. 1B). NDVI was highest at the unburned site and lowest at the severely burned site. However, differences in NDVI across the burn severity gradient were more pronounced in the beginning of the growing season and decreased as the vegetation recovered at the moderately and severely burned sites. For example, tower NDVI at the moderately burned site was 31% lower than the unburned site in June (DOY: 153–182) and 12% lower than the unburned site in August (DOY: 214–244). Seasonal patterns in MODIS, Unispec, and tower NDVI were similar, but tower NDVI was lower than Unispec and MODIS NDVI throughout the growing season (Table 1).

Differences in surface greenness among sites were much more pronounced for EVI and EVI2 than for NDVI (Fig. 1C). Surface greenness, as measured by MODIS and Unispec EVI and tower EVI2, was lowest at the severely burned site and highest at the unburned site, and followed similar seasonal patterns observed for albedo and NDVI. Tower EVI2 in August at the moderately burned site was 34% lower than the unburned site, and 66% lower than the unburned site at the severely burned site. Seasonal patterns for Unispec and MODIS EVI were similar to those observed for tower EVI2, but tower EVI2 was lower than Unispec and MODIS EVI. The slope of the relationship and the RSME between tower derived EVI (i.e. EVI2) and MODIS or Unispec EVI did not substantially differ when EVI2 rather than EVI was used in the comparison. This indicates that EVI and EVI2 are functionally equivalent and may be used interchangeably at these sites (Table 1).

Table 1
Correlations between radiation tower derived vegetation indices and vegetation indices derived from MODIS and Unispec data. All regressions are constrained with a zero intercept and are significant at the 95% confidence level.

Vegetation indices comparisons	MODIS			Unispec		
	Slope	R^2	RSME	Slope	R^2	RSME
NDVI vs. tower NDVI	0.79	0.79	0.12	0.89	0.91	0.06
EVI vs. tower EVI2	0.84	0.95	0.04	0.78	0.95	0.06
EVI2 vs. tower EVI2	0.84	0.95	0.04	0.79	0.98	0.06

3.2. *Relationships between surface greenness and LAI in burned and unburned tundra*

Relationships between surface greenness and LAI in burned and unburned tundra were dependent on the metric used to determine surface greenness (Fig. 2). NDVI was positively related to LAI in burned (Slope of line [β_1]: 0.72; r^2: 0.62; $p < 0.001$) and unburned (β_1: 1.99; r^2: 0.41; $p < 0.001$) tundra, but the slopes of these relationships were significantly different for burned and unburned tundra (ANCOVA; $F_{1,143}$: 18.51; $p < 0.001$) (Fig. 2A). EVI2 also was positively related to LAI in burned (β_1: 1.40; r^2: 0.58; $p < 0.001$) and unburned (β_1: 1.80; r^2: 0.40; $p < 0.001$) tundra, and the slopes of these relationships did not differ significantly between sites (ANCOVA; $F_{1,143}$: 2.08; p: 0.15) (Fig. 2B).

4. Discussion

We assessed the utility of NDVI and EVI2 derived from solar and photosynthetically active radiation fluxes to capture the seasonal pattern and differences in surface greenness across the burn severity gradient. Tower derived vegetation indices were slightly lower than observed with MODIS and Unispec as noted in previous work (see Wilson and Meyers, 2007), and may result from differences in the spectral response of the sensors. Tower EVI2

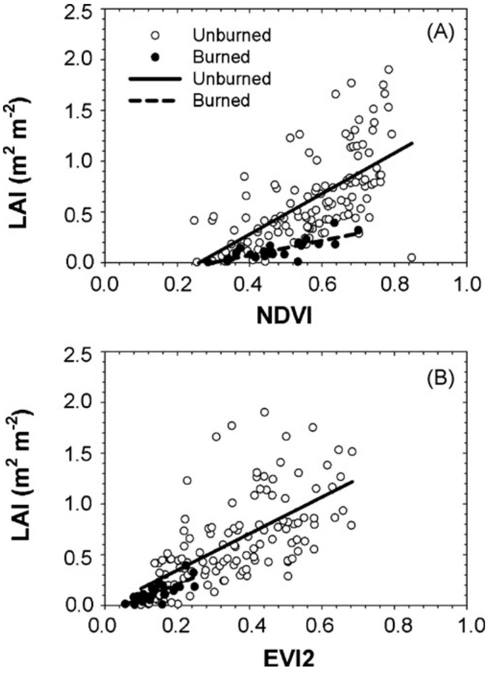

Fig. 2. Relationships between NDVI and LAI (A) and EVI2 and LAI (B) for burned (closed circles/solid line) and unburned (open circles/hatched line) tundra. All regressions are significant at the 95% confidence level.

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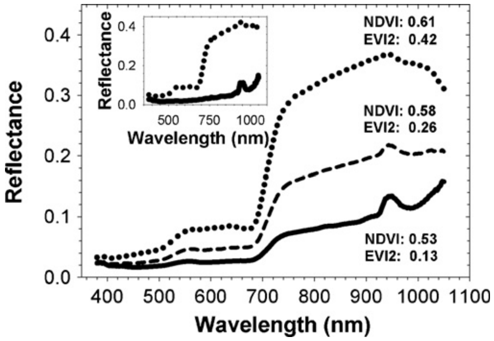

Fig. 3. Unispec spectra for the severe (solid line), moderate (hatched line), and unburned (dotted line) sites on day of year 219 (8/6/2008). NDVI and EVI2 for each site are located next to the associated spectra. Unispec endmember spectra for green tundra (dotted line) and burned soil (solid line) is shown in the inset plot.

performed slightly better than tower NDVI when comparing indices to corresponding MODIS and Unispec derived vegetation indices, with EVI2 having higher correlation coefficients and lower RSME than NDVI (Table 1). Differences in NDVI among sites were smaller than observed for EVI (Fig. 1), and the relationships between surface greenness and LAI differed for the unburned and burned sites for NDVI, but not EVI2 (Fig. 2). These differences indicate that NDVI is limited in its ability to detect differences in leaf area across a burn severity gradient.

4.1. Why does EVI2 perform better than NDVI?

Vegetation indices take advantage of the NIR reflective properties of foliage to derive proxies of surface greenness, which are then related to leaf area or canopy physiology. However, the spectral reflectance of a surface results from a mixture of green vegetation and soil ‘‘background’’ reflectance. Green vegetation displays a rapid increase in reflectance from the red to NIR wavelengths, and is more reflective at these wavelengths than burned soil (Fig. 3 inset). The dark soils at the burned sites produced spectra that were less reflective in the red wavelengths, while the low leaf area produced spectra that were less reflective in the NIR (Fig. 3). Because NDVI depends on the difference between the NIR and red reflectance (i.e. the ‘‘red shoulder’’ of vegetation), as well as the sum of these bands (Eq. (1)), the decrease in red reflectance at the burn sites artificially increased NDVI by disproportionately decreasing the denominator of the NDVI equation relative to the red shoulder. Although EVI2 uses the same information as NDVI, the additional weight on the red reflectance in the denominator of Eq. (3) allows EVI2 to be less sensitive to soil darkening. Increases in NDVI from the darkening of soil can be substantial (Huete, 1988), and in this case, produced similar NDVIs for different surface spectra (Fig. 3), and resulted in separate relationships between NDVI and LAI for the burned and unburned tundra (Fig. 2).

4.2. Implications

The implementation of EVI2 to radiation measurements has several advantages over NDVI and could be used to monitor vegetation phenology and activity across a variety of ecosystems. Both EVI and EVI2 are less sensitive to background reflectance, and the application of EVI2 to radiation measurements presents an added bonus to monitoring because EVI is a better predictor of Gross Primary Productivity (GPP) than NDVI (Xiao et al., 2005). Canopy reflectance and NDVI also are influenced by other factors that affect background reflectance, including bright soils and non-photosynthetically active vegetation (i.e. litter and woody tissues) (Huete, 1988; Van Leeuwen and Huete, 1996; Rocha et al., 2008). Consequently, we encourage the use of EVI2 and express caution on the use of NDVI to track vegetation following fire or when using a single NDVI–LAI relationship for vegetation with different background reflectance.

Acknowledgements

We thank the Toolik Lake Field Station for providing support and logistics, Jen Peters for assistance in the field, Natalie Boelman for providing the ASD spectroradiometer, and Ed Rastetter for editorial comments. This work was supported by NSF grants #0632139 (OPP-AON), #0808789 (OPP-ARCSS SGER), #0829285 (DEB-NEON SGER), and #0423385 (DEB-LTER) to the MBL.

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