ANPP ESTIMATES FROM NDVI FOR THE CENTRAL GRASSLAND REGION OF THE UNITED STATES

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Abstract. Several studies have suggested the existence of a positive relationship between the Normalized Difference Vegetation Index (NDVI) derived from AVHRR/NOAA satellite data and either biomass or annual aboveground net primary production (ANPP) for different geographic areas and ecosystems. We calibrated a 4-yr average of the integral of the NDVI (NDVI-I) using spatially aggregated values of ANPP. We also provided an estimate of the energy conversion efficiency coefficient ($\varepsilon$) of Monteith’s equation. This is the first attempt to calibrate a standard NDVI product for temperate perennial grasslands.

We found a positive and statistically significant relationship between NDVI-I and ANPP for grassland areas with mean annual precipitation between 280 and 1150 mm, and mean annual temperature between 4°C and 20°C. Depending on the method used to estimate the fraction of photosynthetic active radiation, the energy conversion efficiency coefficient was constant (0.24 g C/MJ), or varied across the precipitation gradient, from 0.10 g C/MJ for the least productive to 0.20 g C/MJ for the most productive sites.

Key words: absorbed photosynthetic active radiation; energy conversion efficiency coefficient; grasslands; Normalized Difference Vegetation Index; net primary production; remote sensing.

The ability to translate spectral data to biologically meaningful variables is a key step in increasing the use and value of satellite information. Theoretical work provides strong support for the interpretation of the Normalized Difference Vegetation Index (NDVI) as a measure of carbon flux through ecosystems. Sellers (1987) found that indices based on reflectance in the red and infrared bands are linear indicators of absorbed photosynthetic active radiation (APAR). Sellers et al. (1992) concluded that spectral vegetation indices obtained from coarse resolution satellite data may provide good areally integrated estimates of photosynthesis.

The relationship between NDVI and APAR has been extensively documented (Gallo et al. 1985, Goward et al. 1994, Law and Waring 1994) and provides the theoretical connection between net primary production (NPP) and NDVI through Monteith’s (1981) equation:

$$ NPP = \varepsilon \times \int APAR, $$

where $\varepsilon$ is the energy conversion efficiency (in grams per megajoule) and $\int$ the integral over the year. APAR is given by:

$$ APAR = FPAR \times PAR, $$

where PAR is the photosynthetic active radiation and FPAR the fraction of the PAR intercepted by the green vegetation. Dye and Goward (1993) and Sellers et al. (1994) showed that FPAR can be estimated from NDVI.

The Monteith coefficient $\varepsilon$ is a critical parameter for models that estimate NPP from remotely sensed data (Potter et al. 1993, Ruimy et al. 1994). Field et al. (1995) showed that the current versions of these models differ by a factor of two in the value of $\varepsilon$ for temperate grasslands.

The relationship between NDVI and ANPP is not linear over the entire range of ANPP. For biomes with high ANPP, this relationship becomes saturated (Box et al. 1989). The relationship between ANPP and NDVI is also not always strong. For biomes with low ANPP or biomass, NDVI is influenced by the spectral characteristics of the soil, and the signal associated with the vegetation can be difficult to separate from the influence of the background (Huete 1989). The NDVI may not provide reliable estimates of NPP in evergreen vegetation, where the seasonal patterns of leaf area index and carbon gains are not coupled (Gamon et al. 1995). Grasslands lie in between the extremes of ANPP, and the development of the canopy and photosynthetic activities tend to be in synchrony. Therefore, grasslands appear to be one of the most suitable biomes to derive quantitative estimates of ANPP from NDVI data. In this paper we present an empirical calibration of the relationship between the annual integral of NDVI (NDVI-I) and ANPP for the Central Grassland Region of the United States. We calibrated a 4-yr average of the NDVI-I (AVHRR/NOAA 1.1 km data set) using spatially aggregated values of ANPP from rangeland survey data obtained from the Natural Resource Conservation Service (NRCS). We also provide an estimate of the energy conversion efficiency coefficient (ε) of Monteith’s equation (Eq. 1). This is the first attempt to calibrate a standard NDVI product for temperate perennial grasslands.

Methods

Across the Central Grassland Region, we identified 19 sites corresponding to areas of low human impact, such as experimental sites and National Grasslands, that encompassed the major grassland types of the region. Thus, the sites are our best representation of the potential vegetation of the area. Sites were ≥9 km² in size. We used biweekly (once every two weeks) maximum NDVI composites of 1-km resolution for the contiguous United States from 1990, 1991, 1992, and 1993 obtained from Earth Resources Observation System (EROS; South Dakota, USA; see Eidenshink 1992). The climatic conditions for these 4 yr were similar to the long-term averages. For the 19 sites, the 4-yr average precipitation differed by <10% from the long-term mean annual precipitation. The NDVI was computed from spectral data of channel 1 (red, of wavelength 580–680 nm) and channel 2 (infrared, of wavelength 725–1100 nm) from the AVHRR/NOAA 11 satellite (NDVI = [(Reflectance in Channel 2 – Reflectance in Channel 1)]/(Reflectance in Channel 1 + Reflectance in Channel 2)). The annual integral of NDVI (NDVI-I) was calculated by summing the products of the NDVI for each date and the proportion of the year covered for each composite (usually 15 d or 0.0411). Image processing was performed using ERDAS 7.5 software (ERDAS Incorporated, Atlanta, Georgia).

Aboveground net primary production data were obtained from NRCS range site descriptions (USDA Soil Conservation Service 1967). NRCS range sites represent the potential native plant community of well-managed grazing lands in the absence of abnormal disturbance and other management regimes. Range sites are unique in total ANPP and plant community composition. Range site descriptions include ANPP for favorable, normal, and unfavorable years; we used the ANPP in normal years for our analysis. Range site data have been used in other studies to examine ANPP and plant community composition for the Central Grassland Region (Sala et al. 1988, Brown 1993, Fan 1993, Epstein et al. 1997). Range site descriptions were extended to larger areas using NRCS State Soil Geographic (STATSGO) databases (USDA Soil Conservation Service 1991). STATSGO databases divide states into polygons of similar aggregate soil characteristics called Soil Associations (SA). Each SA is composed of several range sites and includes the areal extent of each range site within the SA. The minimum size of a SA is 625 ha. Thus, ANPP for a SA can be calculated as the weighted average of the ANPP values for each of the component range sites. Our ANPP database was constructed using ARC/INFO Version 6.1.1 (ESRI, Redlands, California). Even though the ANPP data are >20 yr old, they show a high correlation with more recent estimates. The predictions of the Sala et al. (1988) model (based on the NRCS ANPP data) showed a high correlation with recent estimates of ANPP for grasslands of the Northern Hemisphere (J. M. Paruelo, unpublished data).

We digitized circular areas of 9 km² to represent each of our 19 sites throughout the Central Grassland Region. These areas were intersected with the spatial ANPP database. If the 9 km² area overlayed more than one SA, the ANPP value for the site was calculated as the weighted average of ANPP for the intersected SAs. Linear regression analyses were performed in SAS (SAS 1988) using the NDVI-I as the dependent variable and ANPP as the independent variable. Non-linear models were fit using logarithmic transformations of NDVI-I and ANPP. The models were inverted in order to obtain estimates of ANPP from NDVI-I data. The confidence intervals (CI) of the inverted models (P = 0.95) were compared to field estimates of the temporal and spatial variability of ANPP.

For each of the 19 sites we generated daily data of photosynthetically active radiation (PAR) for 20 yr us-
FIG. 1. Relationship between annual aboveground net primary production (ANPP; average values for normal years derived from NRCS rangeland survey data) and the annual integral of NDVI (NDVI-I) derived from AVHRR data (average of 4 yr) for selected sites across the Central Grassland Region of the United States. Part (a) shows the linear model (NDVI-I = 0.10 + 0.00048 × ANPP; n = 19, r² = 0.89, P < 0.0001), and (b) shows a power function (NDVI-I = 0.0163 × ANPP⁰⁰⁰³; n = 19, r² = 0.93, P < 0.0001). Dotted lines correspond to the 95% confidence intervals. Part (c) corresponds to the inverted models, the solid line to the linear model, and the dotted line to the curvilinear model. The numbers indicate the site to which each point corresponds: 1. Cottonwood (South Dakota [SD]; 101.87° W, 43.95° N); 2. Dickinson (North Dakota [ND]; 102.82° W, 46.90° N); 3. Hays (Kansas [KS]; 99.38° W, 38.87° N); 4. Osage (Oklahoma [OK]; 96.55° W, 36.95° N); 5. Pantex (Texas [TX]; 101.53° W, 35.30° N); 6. Central Plains Experimental Range (Colorado [CO]; 104.60° W, 40.82° N); 7. S. H. Ordway Memorial Prairie (SD, 99.10° W, 45.33° N); 8. Fort Keogh Range Research Laboratory (Montana [MT]; 105.88° W, 46.30° N); 9. Konza Prairie (KS; 96.60° W, 39.10° N); 10. Sevilleta (New Mexico [NM]; 106.68° W, 34.33° N); 11. Arapaho (Nebraska [NE]; 101.80° W, 41.55° N); 12. Black Gap Wildlife Area (TX; 102.92° W, 29.58° N); 13. Snyder (TX; 101.18° W, 32.97° N); 14. Oklahoma State University Agricultural Research Range (OK; 97.23° W, 36.05° N); 15. Alzada (Missouri [MO]; 104.47° W, 45.03° N); 16. Springfield (CO; 102.73° W, 37.37° N); 17. Eastern Colorado Range Station (CO; 103.17° W, 40.38° N); 18. El Paso (CO; 104.50° W, 38.55° N); 19. Lincoln County (NM; 105.08° W, 34.28° N).

We estimated ε as the slope of the relationship of Eq. 1, where APAR was estimated using PAR generated by the WEATHERMAN program and FPAR estimated from Eqs. 3 and 4.

Results and discussion

We found a positive and statistically significant relationship between NDVI-I and ANPP for grassland areas with mean annual precipitation between 280 and 1150 mm, and mean annual temperature between 4°C and 20°C (Fig. 1a). The relationship between ANPP and NDVI-I was slightly better using a power function compared to a linear model (Fig. 1b; r² = 0.92 and r² = 0.89, respectively). This suggests a slight saturation of NDVI-I for sites with high primary production.
et al. (1989), for a broader range of biomes, also found that a saturation model fit ANPP–NDVI-I data.

Inverting the equations yields models of ANPP as a function of NDVI (Fig. 1c). These are the only available models that estimate ANPP from NDVI for temperate grasslands. When the linear model was inverted (ANPP = −181 + 1864 × NDVI-I; \( r^2 = 0.89, n = 19, P < 0.0001 \)), the confidence interval of ANPP (\( P = 0.95 \)) near the midpoint of the NDVI range (Cottonwood site, Number 1 in Fig. 1) was ±44 g/m². When the power function model was inverted (ANPP = 3803 × NDVI-I\(^{−1.9023}; r^2 = 0.92, n = 19, P < 0.0001 \)), the CI was ±35 g/m² at the midpoint of the NDVI range. In both cases, the CI corresponded to ~20% of the ANPP estimate. At the Central Plains Experimental Station (CPER), a low productivity site (Number 6 in Fig. 1), the CI was ±53 g/m² or 42% of the ANPP estimate using the linear model and ±28 g/m² or 22% of the ANPP estimate using the curvilinear model. Field estimates of ANPP at the CPER over 52 yr have a CI of 42% of the average value (Lauenroth and Sala 1992). Thus, the estimates of ANPP derived from our models showed a degree of certainty similar to that commonly found in field estimates. Field estimates of peak biomass (ANPP) for sites in the Central Grassland Region have CIs ranging between 18 and 53% of the estimate (Lauenroth and Whitman 1977, Barnes et al. 1983).

The coefficients of determination of our models were higher than those of relationships fit for annual grasslands of the Sahel in various studies (Table 1). The linear model predicted an NDVI-I of 0.10 at ANPP of 0. The corresponding value for the non-linear model was 0.016, which lies in the range of values found for annual grasslands of the Sahel (Table 1). For North American shrubland areas with lower values of ANPP than the sites considered here (e.g., Rock Valley, Nevada, with an ANPP of 20 g/m² [Webb et al. 1978]) NDVI-I averaged 0.07 (\( n = 4 \); J. M. Paruelo and W. K. Lauenroth, unpublished data), which corresponds to a negative ANPP for the linear model. The ANPP estimated from the power function model for Rock Valley was 22 g/m². This gives additional support for using the non-linear model in ANPP estimates, particularly at the lower extreme of the domain. The slope of our linear model lies in the range of values of models for annual grasslands of the Sahel by several authors (Table 1). The slope of the model presented by Box et al. (1989) for a broader range of biomes was lower than the slope for the Central Grassland Region. To what extent these differences are related to variation in the structure of vegetation or in the data used remains an open question.

The relationship between ANPP and APAR (FPAR × PAR) was described by a linear model (ANPP = −8.59 + 0.24 × APAR; \( r^2 = 0.93, n = 19, P < 0.0001 \)) when FPAR was estimated using Eq. 3. The energy conversion efficiency (\( \varepsilon \)) consequently showed a constant value of 0.24 g C/MJ for the range of grasslands analyzed. When FPAR was estimated using Eq. 4, a power function model was the best descriptor of the relationship between APAR and ANPP (ANPP = 0.00422 × APAR\(^{1.5652}; r^2 = 0.90, n = 19, P < 0.0001 \)). In this case, \( \varepsilon \) showed an increase from 0.10 g C/MJ for the less productive sites to 0.20 g C/MJ for the most productive sites. These values agree with the estimates derived from the Carnegie, Ames, Stanford Approach (CASA) model for temperate grasslands (0.277 g C/MJ) and for deserts (0.160 g C/MJ) (Field et al. 1995).

Our results suggest that a simple relationship allows for a relatively accurate description of the spatial heterogeneity of ANPP using NDVI data in the Central Grassland Region. Even though NDVI and ANPP data do not correspond to the same time period, the comparison of averages over many years minimizes this problem. We recognize the limitations in extrapolating models beyond their boundaries. Deviations may be expected for areas where the original plant communities have been replaced. Furthermore, our models are based on spatial data (NDVI-I and ANPP averaged over

<table>
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<tr>
<th>Vegetation type</th>
<th>a</th>
<th>b</th>
<th>r²</th>
<th>n</th>
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<td>0.0109</td>
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<td>0.00038</td>
<td>0.59</td>
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<td>−0.1288 to 0.2083</td>
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<tr>
<td>Broad range of biomes</td>
<td>0 (forced)</td>
<td>0.00016</td>
<td>0.51</td>
<td>95</td>
<td>Box et al. (1989)</td>
</tr>
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</table>

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years for different sites in the Central Grassland Region) and may not be appropriate for interannual estimates of ANPP from NDVI-I for a particular site (Lauenroth and Sala 1992).

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**LITERATURE CITED**


