Ecology, 78(3), 1997, pp. 953–958

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

JOSÉ M. PARUELO,[1,4] HOWARD E. EPSTEIN,[2] WILLIAM K. LAUENROTH,[1,3] AND INGRID C. BURKE[2,3]

[1]*Department of Rangeland Ecosystem Science, Colorado State University, Fort Collins, Colorado 80523 USA*
[2]*Department of Forest Science, Colorado State University, Fort Collins, Colorado 80523 USA*
[3]*Natural Resources and Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80523 USA*

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 ingegral of the NDVI (NDVI-I) using spatially aggregated values of ANPP. We also provided an estimate of the energy conversion efficiency coefficient (ε) 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° and 20°C. Depending on the method used to estimate the fraction of photosynthetic active radiation, the energy conversion officency 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:

$$\text{NPP} = \varepsilon \times [\textstyle\int \text{APAR}], \quad (1)$$

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

$$\text{APAR} = \text{FPAR} \times \text{PAR}, \quad (2)$$

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 ε 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 ε for temperate grasslands.

Several studies have suggested the existence of a positive relationship between NDVI derived from Advanced Very High Resolution Radiometer/National Oceanic and Atmospheric Agency (AVHRR/NOAA) satellite data and either biomass or annual aboveground net primary production (ANPP) for different geographic areas and ecosystems (Goward et al. 1985, Tucker et al. 1985, Box et al. 1989, Burke et al. 1991, Diallo et al. 1991, Prince 1991, Wylie et al. 1991, Chong et al. 1993, Hobbs 1995). Other studies have related NDVI with atmospheric CO_2 concentrations (Tucker et al. 1986, Cihlar et al. 1992), precipitation (Nicholson et al. 1990, Paruelo et al. 1993, Potdar et al. 1993, Nicholson and Farar 1994, Paruelo and Lauenroth 1995), or evapotranspiration (Running and Nemani

Manuscript received 8 November 1995; revised 8 March 1996; accepted 26 March 1996.

[4] Present address: Depto de Ecología, Facultad de Agronomía—Universidad de Buenos Aires, Av. San Martín 4453,1417 Buenos Aires, Argentina.

1988, Cihlar et al. 1991). None of these broad scale studies have provided an estimate of ϵ for temperate perennial 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 represention of the potential vegetation of the area. Sites were $\geq$9 km^2 in size. We used biweekly (once every two weeks) maximum NDVI composites of 1-km resolution for the conterminous 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 km^2 to represent each of our 19 sites throughout the Central Grassland Region. These areas were intersected with the spatial ANPP database. If the 9 km^2 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-

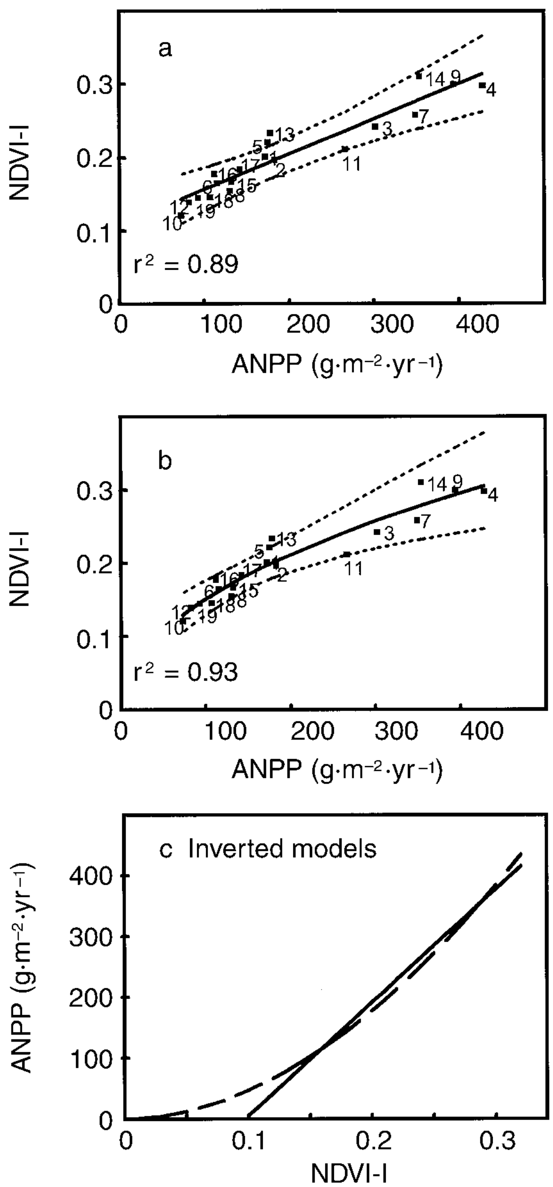

FIG. 1. Relationship between annual aboveground net primary production (ANPP; average values for normal years derived from NRCS rangeland survey data) and the annual integral of NDVI (NDVI-I) derived from AVHRR data (average of 4 yr) for selected sites across the Central Grassland Region of the United States. Part (a) shows the linear model (NDVI-I = 0.10 + 0.00048 × ANPP; n = 19, r^2 = 0.89, $P < 0.0001$), and (b) shows a power function (NDVI-I = 0.0163 × $\text{ANPP}^{0.4831}$; n = 19, r^2 = 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).

ing a widely used weather generator program (WEATHERMAN; Pickering et al. 1994). This program generates daily data of precipitation, temperature, and radiation using a Markov chain approach and parameters derived from monthly values of precipitation, temperature, and cloudiness. Richardson (1985) and Meinke et al. (1995) showed that the algorithm used by the WEATHERMAN program produces reliable estimates of radiation. We calculated PAR for a monthly time step and averaged the values over the 20 yr. We estimated the fraction of PAR absorbed for each month from the NDVI data using the formulas presented by Potter et al. (1993) and Ruimy et al. (1994). Potter et al. (1993) calculated FPAR as:

$$\text{FPAR} = \text{SR}/(\text{SR}_{max} - \text{SR}_{min}) - \text{SR}_{min}/(\text{SR}_{max} - \text{SR}_{min}), \quad (3)$$

where SR is the ratio of the red and infrared bands of the satellite (SR = [1 + NDVI]/[1 − NDVI]). SR_{max} and SR_{min} were set to 4.14 and 1.08 (Potter et al. 1993). Ruimy et al. (1994) calculated FPAR assuming a linear relationship with NDVI:

$$\text{FPAR} = -0.025 + 1.25 \times \text{NDVI}. \quad (4)$$

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° 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; r^2 = 0.92 and r^2 = 0.89, respectively). This suggests a slight saturation of NDVI-I for sites with high primary production. Box

TABLE 1. The y intercept (a), slope (b), coefficient of determination (r^2), and number of sites (n) for several models of the form NDVI = $a + b \cdot$ANPP from the literature.

Vegetation type	a	b	r^2	n	References
Perennial grasslands (North America)	0.1038	0.00048	0.89	19	This study
Annual grasslands (Sahel)	0.0148	0.00140	0.65	17	Diallo et al. (1991)
	0.0109	0.00113	0.82	17	Diallo et al. (1991)
	−0.3309	0.00038	0.59	27	Diallo et al. (1991)
	−0.3073	0.00036	0.66	27	Diallo et al. (1991)
	−0.1288 to 0.2083	0.00101	0.80	172	Prince (1991)
	0.0123	0.00140	0.69	204	Tucker et al. (1985)
	0.0261	0.00074	0.68	20	Wyllie et al. (1991)
	0.0301	0.00038	0.91	21	Wyllie et al. (1991)
	0.0330	0.00075	0.73	30	Wyllie et al. (1991)
Broad range of biomes	0 (forced)	0.00016	0.51	95	Box et al. (1989)

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 = $-181 + 1864 \times$ 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/m^2. When the power function model was inverted (ANPP = $3803 \times$ NDVI-I$^{1.9028}$; $r^2 = 0.92$, $n = 19$, $P < 0.0001$), the CI was ± 35 g/m^2 at the midpoint of the NDVI range. In both cases, the CI corresponded to $\approx$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/m^2 or 42% of the ANPP estimate using the linear model and ± 28 g/m^2 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/m^2 [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/m^2. 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 $\times$ PAR) was described by a linear model (ANPP = $-8.59 + 0.24 \times$ APAR; $r^2 = 0.93$, $n = 19$, $P < 0.0001$) when FPAR was estimated using Eq. 3. The energy conversion efficiency (ε) 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 ANPP and APAR (ANPP = $0.00422 \times$ APAR$^{1.5652}$; $r^2 = 0.90$, $n = 19$, $P < 0.0001$). In this case, ε 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 Carnagie, 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 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).

Acknowledgments

This study was funded by the Long Term Ecological Research-U.S. National Science Foundation (LTER-NSF) grant BSR 90-11659 and by the NSF grant BSR 91-06183. J. M. Paruelo was supported by Consejo Nacional de Investigaciones Cientificas y Técnicas (CONICET) and Universidad de Buenos Aires (Argentina). Esteban Jobbagy provided useful comments.

Literature Cited

Barnes, P. W., L. L. Tiezen, and D. J. Ode. 1983. Distribution, production, and diversity of C_3 and C_4 dominated communities in a mixed prairie. Canadian Journal of Botany **61**:741–751.

Box, E. O., B. N. Holben, and V. Kalb. 1989. Accuracy of the AVHRR Vegetation Index as a predictor of biomass, primary productivity and net CO_2 flux. Vegetatio **80**:71–89.

Brown, D. A. 1993. Early nineteenth-century grasslands of the midcontinent plains. Annals of the Association of American Geographers **83**:589–612.

Burke, I. C., T. G. F. Kittel, W. K. Lauenroth, P. Snook, C. M. Yonker, and W. J. Parton. 1991. Regional analysis of the Central Great Plains. BioScience **41**:685–692.

Chong, D. L. S., E. Mougin, and J. P. Gastellu-Etchegorry. 1993. Relating the Global Vegetation Index to net primary productivity and actual evapotranspiration over Africa. International Journal of Remote Sensing **14**:1517–1546.

Cihlar, J., P. H. Caramori, P. H. Schuepp, R. L. Desjardins, and J. I. MacPherson. 1992. Relationship between satellite-derived vegetation indices and aircraft-based CO_2 measurements. Journal of Geophysical Research **97**:18515–18521.

Cihlar, J., L. St.-Laurent, and J. A. Dyer. 1991. Relation between the Normalized Difference Vegetation Index and ecological variables. Remote Sensing of Environment **35**:279–298.

Diallo, O., A. Diouf, N. P. Hanan, A. Ndiaye, and Y. Prevost. 1991. AVHRR monitoring of savanna primary production in Senegal, West Africa: 1987–1988. International Journal of Remote Sensing **12**:1259–1279.

Dye, D. G., and S. N. Goward. 1993. Photosynthetically active radiation absorbed by global land vegetation in August 1984. International Journal of Remote Sensing **14**:3361–3364.

Eidenshink, J. C. 1992. The 1990 conterminous US AVHRR data set. Photogrammetric Engineering and Remote Sensing **58**(6):809–813.

Epstein, H. E., W. K. Lauenroth, I. C. Burke, and D. P. Coffin. 1997. Regional productivity patterns of C_3 and C_4 functional types in the Great Plains of the United States. Ecology **78**, *in press.*

Fan, W. 1993. Regional analysis of plant species and environmental variables in eastern Colorado. Dissertation. Colorado State University, Fort Collins, Colorado, USA.

Field, C. B., J. T. Randerson, and C. M. Malmstron. 1995. Global net primary production: combining ecology and remote sensing. Remote Sensing of Environment **51**:74–88.

Gallo, K. P., C. S. T. Daughtry, and M. E. Bauer. 1985. Spectral estimation of absorbed photosynthetically active radiation in corn canopies. Remote Sensing of Environment **17**:221–232.

Gamon, J. A., C. B. Field, M. L. Goulden, K. L. Griffin, A. E. Hartley, G. Joel, J. Peñuelas, and R. Valentini. 1995. Relationships between NDVI, canopy structure, and photosynthesis in three Californian vegetation types. Ecological Applications **5**:28–41.

Goward, S. N., S. J. Tucker, and D. G. Dye. 1985. North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. Vegetatio **64**:3–14.

Goward, S. N., R. H. Waring, D. G. Dye, and J. Yang. 1994. Ecological remote sensing at OTTER: satellite macroscale observations. Ecological Applications **4**:322–343.

Hobbs, T. J. 1995. The use of NOAA-AVHRR NDVI data to assess herbage production in the arid rangelands of Central Australia. International Journal of Remote Sensing **16**:1289–1302.

Huete, A. R. 1989. Soil influences in remotely sensed vegetation-canopy spectra. Pages 107–141 *in* G. Asrar, editor. Theory and applications of optical remote sensing. John Wiley and Sons, New York, New York, USA.

Lauenroth, W. K., and O. E. Sala. 1992. Long-term forage production of North American shortgrass steppe. Ecological Applications **2**:397–403.

Lauenroth, W. K., and W. C. Whitman. 1977. Dynamics of dry matter production in a mixed-grass prairie in western North Dakota. Oecologia **27**:339–351.

Law, B. E., and R. H. Waring. 1994. Remote sensing of leaf area index and radiation intercepted by understory vegetation. Ecological Applications **4**:272–279.

Meinke, H., P. S. Carberry, M. R. McCaskill, M. A. Hills, and I. McLeod. 1995. Evaluation of radiation and temperature data generators in the Australian tropics and subtropics using crop simulation models. Agricultural and Forest Meteorology **72**:295–316.

Monteith, J. L. 1981. Climatic variation and the growth of crops. Quarterly Journal of the Royal Meteorological Society **107**:749–774.

Nicholson, S. E., M. L. Davenport, and A. R. Malo. 1990. A comparison of the vegetation response to rainfall in the Sahel and East Africa, using Normalized Difference Vegetation Index from NOAA AVHRR. Climatic Change **17**:209–241.

Nicholson, S. E., and T. J. Farrar. 1994. The influence of soil type on the relationships between NDVI, rainfall, and soil moisture in semiarid Botswana. I. NDVI response to rainfall. Remote Sensing of Environment **50**:107–120.

Paruelo, J. M., M. R. Aguiar, R. A. Golluscio, R. J. C. Leon, and G. Pujol. 1993. Environmental controls of the NDVI dynamics in Patagonia based on NOAA-AVHRR satellite data. Journal of Vegetation Science **4**:425–428.

Paruelo, J. M., and W. K. Lauenroth. 1995. Regional patterns of NDVI in North American shrublands and grasslands. Ecology **76**:1888–1898.

Pickering, N. B., J. W. Hansen, J. W. Jones, C. M. Wells, V. K. Chan, and D. C. Godwin. 1994. WeatherMan: a utility for managing and generating daily weather data. Agronomy Journal **86**:332–337.

Potdar, M. B., S. S. Pokharna, and V. N. Sridhar. 1993. Response of vegetation in the Thar Desert to monsoon rainfall: an investigation using NOAA AVHRR and meteorological data. Journal of Arid Environments **25**:19–26.

Potter, C. S., J. T. Randerson, C. B. Field, P. A. Matson, P. M. Vitousek, H. A. Mooney, and S. A. Klooster. 1993. Terrestrial ecosystem production: a process model based on global satellite and surface data. Global Biogeochemical Cycles **7**:811–841.

Prince, S. D. 1991. Satellite remote sensing of primary production: comparison of results for Sahelian grasslands 1981–1988. International Journal of Remote Sensing **12**: 1301–1311.

Richardson, C. W. 1985. Weather simulation for crop management models. Transactions of the American Society of Agricultural Engineering **28**:1602–1606.

Ruimy, A., B. Saugier, and G. Dedieu. 1994. Methodology for the estimation of terrestrial net primary production from remotely sensed data. Journal of Geophysical Research **99**: 5263–5283.

Running, S. W., and R. R. Nemani. 1988. Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. Remote Sensing of Environment **24**:347–367.

SAS. 1988. SAS/STAT user's guide. Release 6.03. SAS Institute, Cary, North Carolina, USA.

Sala, O. E., W. J. Parton, L. A. Joyce, and W. K. Lauenroth. 1988. Primary production of the central grassland region of the United States. Ecology **69**:40–45.

Sellers, P. J. 1987. Canopy reflectance, photosynthesis, and transpiration. II. The role of biophysics in the linearity of their interdependence. Remote Sensing of Environment **21**: 143–183.

Sellers, P. J., J. A. Berry, G. J. Collatz, C. B. Field, and F. G. Hall. 1992. Canopy reflectance, photosynthesis, and transpiration. III. A reanalysis using improved leaf models and a new canopy integration scheme. Remote Sensing of the Environment **42**:187–216.

Sellers, P. J., C. J. Tucker, G. J. Collatz, S. O. Las, C. O. Justice, D. A. Dazlich, and D. A. Randall. 1994. A global 1° by 1° NDVI data set for climate studies. Part 2: The generation of global fields of terrestrial biophysical parameters from the NDVI. International Journal of Remote Sensing **15**:3519–3545.

Tucker, C. J., I. Y. Fung, C. D. Keeling, and R. H. Gammon. 1986. Relationship between atmospheric CO_2 variations and a satellite-derived vegetation index. Nature **319**:195–199.

Tucker, C. J., C. L. Vanpraet, M. J. Sharman, and G. Van Ittersum. 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–1984. Remote Sensing of Environment **17**:233–249.

USDA (U.S. Department of Agriculture) Soil Conservation Service. 1967. National handbook for range and related grazing lands.

———. 1991. State soil geographic data base (STATSGO): data users guide. Miscellaneous Publication Number **1492**.

Webb, W., S. Szarek, W. K. Lauenroth, R. Kinerson, and M. Smith. 1978. Primary productivity and water use in native forest, grassland, and desert ecosystems. Ecology **59**:1239–1247.

Wylie, B. K., J. A. Harrington Jr., S. D. Prince, and I. Denda. 1991. Satellite and ground-based pasture production in Niger: 1986–1988. International Journal of Remote Sensing **12**:1281–1300.