GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L06407, doi:10.1029/2006GL029127, 2007

A five-year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States

Yingxin Gu,[1] Jesslyn F. Brown,[1] James P. Verdin,[2] and Brian Wardlow[3]

Received 18 December 2006; revised 16 February 2007; accepted 28 February 2007; published 27 March 2007.

[1] A five-year (2001–2005) history of moderate resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) data was analyzed for grassland drought assessment within the central United States, specifically for the Flint Hills of Kansas and Oklahoma. Initial results show strong relationships among NDVI, NDWI, and drought conditions. During the summer over the Tallgrass Prairie National Preserve, the average NDVI and NDWI were consistently lower (NDVI < 0.5 and NDWI < 0.3) under drought conditions than under non-drought conditions (NDVI>0.6 and NDWI>0.4). NDWI values exhibited a quicker response to drought conditions than NDVI. Analysis revealed that combining information from visible, near infrared, and short wave infrared channels improved sensitivity to drought severity. The proposed normalized difference drought index (NDDI) had a stronger response to summer drought conditions than a simple difference between NDVI and NDWI, and is therefore a more sensitive indicator of drought in grasslands than NDVI alone. **Citation:** Gu, Y., J. F. Brown, J. P. Verdin, and B. Wardlow (2007), A five-year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States, *Geophys. Res. Lett.*, *34*, L06407, doi:10.1029/2006GL029127.

1. Introduction

[2] Drought is one of the most costly natural disasters in the United States [*Federal Emergency Management Agency*, 1995; *Wilhite*, 2000]. Traditionally, drought monitoring has been based on weather station observations, which lack the continuous spatial coverage needed to characterize and monitor the detailed spatial pattern of drought conditions. Since the 1970's, hundreds of studies have used satellite land observation data to monitor a variety of dynamic land surface processes [e.g., *Anderson et al.*, 1976; *Reed et al.*,1994; *Yang et al.*, 1998; *Peters et al.*, 2002]. Satellite remote sensing provides a synoptic view of the land and a spatial context for measuring drought impacts.

[3] The normalized difference vegetation index (NDVI), which is the normalized reflectance difference between the near infrared (NIR) and visible red bands [*Rouse et al.*, 1974; *Tucker*, 1979] is used extensively in ecosystem monitoring. The NDVI measures the changes in chlorophyll content (via absorption of visible red radiation) and in spongy mesophyll (via reflected NIR radiation) within the vegetation canopy. As a result, higher NDVI values usually represent greater vigor and photosynthetic capacity (or greenness) of vegetation canopy [*Tucker*, 1979; *Chen and Brutsaert*, 1998]. NDVI's role in drought monitoring and assessment has been described several times during the last decade [*Kogan*, 1991; *Kogan*, 1995; *Yang et al.*, 1998; *McVicar and Bierwirth*, 2001; *Ji and Peters*, 2003; *Wan et al.*, 2004]. Most of these efforts were based on NDVI calculated from data collected by the Advanced Very High Resolution Radiometer (AVHRR) sensor. NDVI has been calculated from AVHRR data for more than 20 years (1981–present), creating a useful time-series for monitoring. However, one limitation of NDVI for drought monitoring is the apparent time lag between a rainfall deficit and NDVI response [*Reed*, 1993; *Di et al.*, 1994; *Rundquist and Harrington*, 2000; *Wang et al.*, 2001].

[4] The normalized difference water index (NDWI) is a more recent satellite-derived index from the NIR and short wave infrared (SWIR) channels that reflects changes in both the water content (absorption of SWIR radiation) and spongy mesophyll in vegetation canopies [*Gao*, 1996]. NDWI calculated from the 500-m SWIR band of MODIS has recently been used to detect and monitor the moisture condition of vegetation canopies over large areas [*Xiao et al.*, 2002; *Jackson et al.*, 2004; *Maki et al.*, 2004; *Chen et al.*, 2005; *Delbart et al.*, 2005]. Because NDWI is influenced by both desiccation and wilting in the vegetation canopy, it may be a more sensitive indicator than NDVI for drought monitoring.

[5] The objective of this study was to investigate and compare satellite-derived methods for measuring and monitoring drought in grasslands over the central Great Plains of the United States. This study includes: (1) the development of a regional climatological time-series database (2001–2005) of MODIS-derived NDVI and NDWI; (2) an evaluation of the relationship between NDVI, NDWI, and climate conditions over grassland; (3) an investigation of additional drought information provided by NDWI versus NDVI, based on a 5-year comparison of the two indices; and (4) the generation of a new vegetation drought index, the normalized difference drought index (NDDI), to investigate drought conditions over the grasslands of the Flint Hills ecoregion.

2. Data and Methodology

[6] MODIS 8-day 500-meter surface reflectance data (MOD09A1, Collection 4) were the basis of this study.

[1]Science Applications International Corporation, US Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, South Dakota, USA.
[2]US Geological Survey Center for Earth Resources Observation and Science, Sioux Falls, South Dakota, USA.
[3]National Drought Mitigation Center, University of Nebraska at Lincoln, Nebraska, USA.

0094-8276/07/2006GL029127$05.00

Figure 1. Locations of Flint Hills ecoregion and Tallgrass Prairie National Preserve site in Kansas, within the larger study area extending from Kansas to northern Texas.

The MODIS data were obtained from the Land Processes Distributed Active Archive System and accessed from the EOS Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). The data were processed as follows: (1) Data from the MODIS tiles (h09v05, h10v04, h10v05, h11v04) were mosaicked. (2) Cloud pixels and "fill value pixels were masked out using the MODIS data quality flags. (3) NDVI and NDWI were calculated according to equations 1 and 2:

$$NDVI = \frac{\rho_{857} - \rho_{645}}{\rho_{857} + \rho_{645}} \quad (1)$$

$$NDWI = \frac{\rho_{857} - \rho_{2130}}{\rho_{857} + \rho_{2130}} \quad (2)$$

where ρ_{645}, ρ_{857}, and ρ_{2130} are the reflectances at 645 nm, 857 nm, and 2130 nm, respectively. (4) NDVI and NDWI data sets were sequentially stacked into a five-year time series (2001–2005). (5) A low-frequency filter was applied to the NDWI image data in order to reduce banding effects in the SWIR image data. (6) Spike points (i.e., abnormally high values) were removed from the NDWI time series using a quality assurance (QA) mask. (7) NDVI and NDWI time series were smoothed using a weighted least-squares approach [*Swets et al.*, 1999] to reduce noise. (8) NDVI and NDWI time series data were extracted over grassland vegetation types as identified in the National Land Cover Dataset (NLCD) [*Vogelmann et al.*, 2001]. (9) NDDI was generated from NDVI and NDWI using the following equation.

$$NDDI = \frac{NDVI - NDWI}{NDVI + NDWI} \quad (3)$$

(10) The Flint Hills ecoregion data were analyzed using a mask from the Omernik ecoregions dataset [*Omernik*, 1987].

3. Study Area

[7] The larger study area in our research extends from Kansas through Oklahoma, into northern Texas (Figure 1). Our initial investigation was focused on the Flint Hills ecoregion (Figure 1) and the Tallgrass Prairie National Preserve site in Chase County, Kansas (identified as a red box in Figure 1). The Tallgrass Prairie National Preserve site was selected for close inspection because it is managed by the National Park Service with a single conservation management strategy. The land cover type of this site is primarily tallgrass prairie. The relatively homogeneous land cover type and single management practice allowed the influence of drought on the grasslands to be isolated from other factors and therefore more effectively studied. The Flint Hills is the largest remaining area of native tallgrass prairie in North America (see Kansas Partners for Fish and Wildlife, U. S. Fish and Wildlife Service: http://kansaspartners.fws.gov/ks3d.htm). Much of the Flint Hills is rangeland and used for grazing.

4. Results and Analysis

4.1. NDVI, NDWI, and Drought Condition Analysis Over the Tallgrass Prairie National Preserve Site (Kansas)

[8] Figure 2a shows the relationship between NDVI and NDWI for individual pixels over the Tallgrass Prairie site (a total of 60 pixels) under different climate conditions for the July 28th composite period (July 28 – August 04) over the five-year study period. The observations in the plot are color-coded by the drought severity designation for that area as determined from U.S. Drought Monitor (USDM) maps (http://drought.unl.edu/dm/monitor.html). The USDM summarizes information from several drought indices and indicators, and provides a weekly overview of drought conditions that is widely used in the United States. The descriptions of the drought severity categories defined by the USDM are listed in Table 1. Figure 2a illustrates that there are strong relationships between NDVI, NDWI, and drought. NDVI and NDWI values were much lower (NDVI < 0.5 and NDWI < 0.3) in the 2002 and 2003 drought years, identified by the USDM as D1 (moderate) and D2 (severe) category droughts. NDVI and NDWI were higher in years that experienced more favourable growing season conditions (NDVI>0.6 and NDWI>0.4), identified as non-drought (D0) by the USDM.

[9] Time series NDVI and NDWI data over the Tallgrass Prairie National Preserve site (averaged value for all pixels) are plotted in Figure 2b. During the summer months (composite periods June 30 to September 28), the NDVI and NDWI values were substantially lower in the drought years (2002 and 2003) than in the non-drought years (2001, 2004, and 2005). The five-year mean NDVI and NDWI values (plotted in yellow in Figure 2b) separate the drought years from the non-drought years. NDWI values decreased more than NDVI values during the severe summer drought of 2003 (60 percent lower than the average versus 30 percent lower than the average), which suggests that

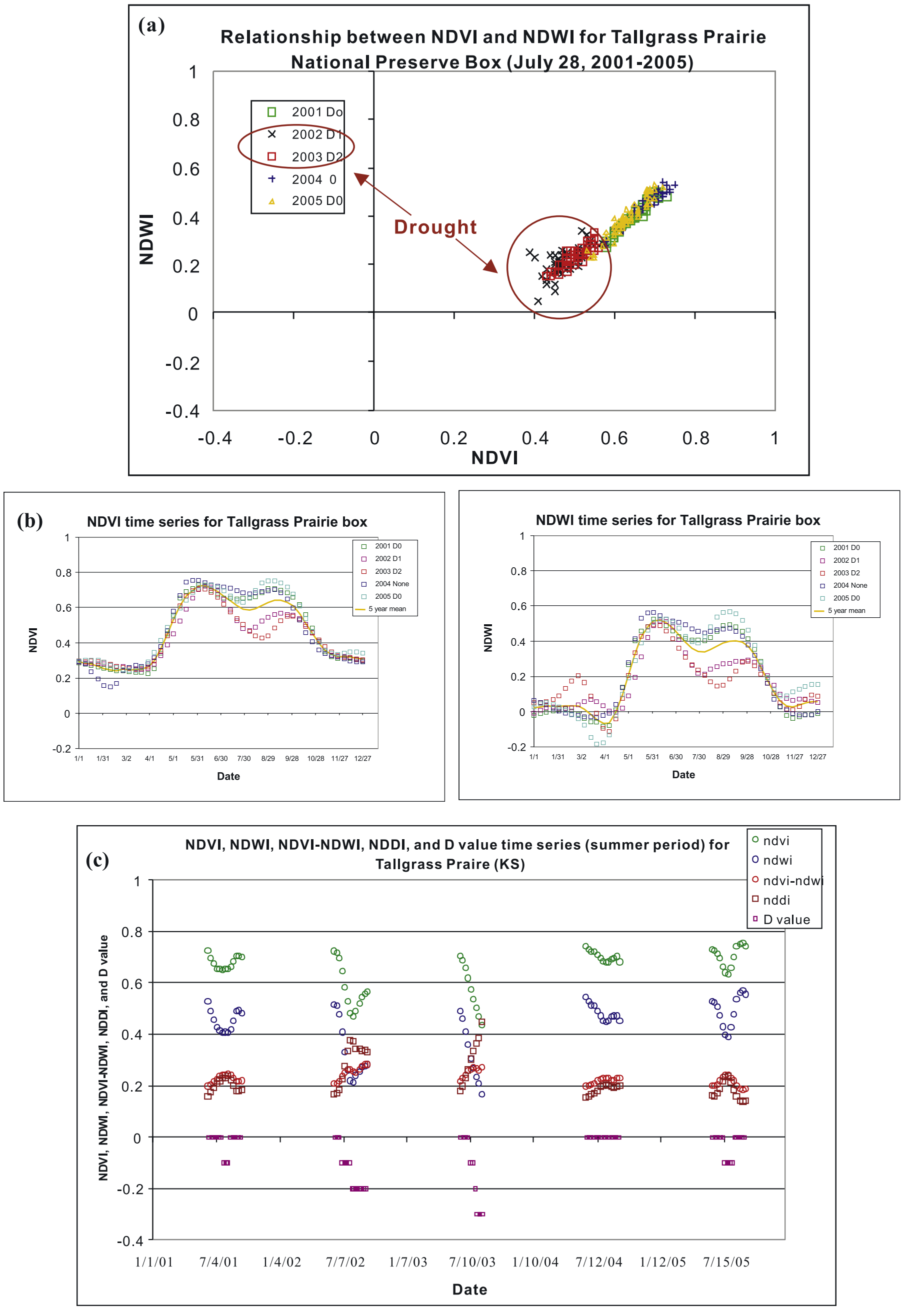

Figure 2. (a) Scatter plot for NDVI and NDWI over Tallgrass Prairie National Preserve site, July 28, 2001–2005. (b) Time series plots of NDVI and NDWI for Tallgrass Prairie National Preserve site (averaged value of the box). (c) Time series plot of NDVI, NDWI, NDVI-NDWI, NDDI, and D value (USDM drought category) for Tallgrass Prairie National Preserve site during the summer (June to September).

Table 1. Drought Categories and the Palmer Drought Severity Index[a]

Drought Class	D Value[b]	Palmer Drought Severity Index	Description
0	0	−0.49 or more	non-drought
D0	−0.1	−0.5 ~ −1.99	abnormally dry
D1	−0.2	−2.0 ~ −2.99	drought-moderate
D2	−0.3	−3.0 ~ −3.99	drought−severe
D3	−0.4	−4.0 or less	drought-extreme
D4	−0.5		drought-exceptional

[a]Drought categories are defined from the USDM.
[b]D value is defined in this paper.

the NDWI was more sensitive than NDVI to drought conditions. The sharper drop in NDWI values means that during the summer drought period, the grassland vegetation had a greater loss in water content than in greenness (i.e., chlorophyll content).

[10] To take advantage of information contained in both NIR and SWIR channels, the difference between NDVI and NDWI for the summer periods was calculated and plotted in Figure 2c. Because drought occurred mainly during the summer, our analysis was restricted to the summer months. The NDVI, NDWI, and corresponding drought severity designations from the USDM (D value) are also plotted in Figure 2c. The NDVI and NDWI values decreased considerably more during the summer composite periods for the 2002 and 2003 droughts compared to the other years. The NDVI-NDWI difference also slightly increased during drought years and the difference values were consistently above the five year mean (Figure 2c) when the mid-summer drought conditions persisted. In an effort to magnify the difference between NDVI and NDWI, NDDI was calculated using equation 3, which combines information from visible, NIR, and SWIR channels. The sharp increase in NDDI values during summer drought periods (Figure 2c) demonstrated that the NDDI had a stronger drought signal in grasslands than the NDVI-NDWI difference alone.

4.2. NDVI, NDWI, and Drought Condition Analysis Over the Flint Hills Ecoregion

[11] To investigate NDVI, NDWI, and NDDI over a larger area with more variability in rainfall and land management practices, we extracted random grassland pixels

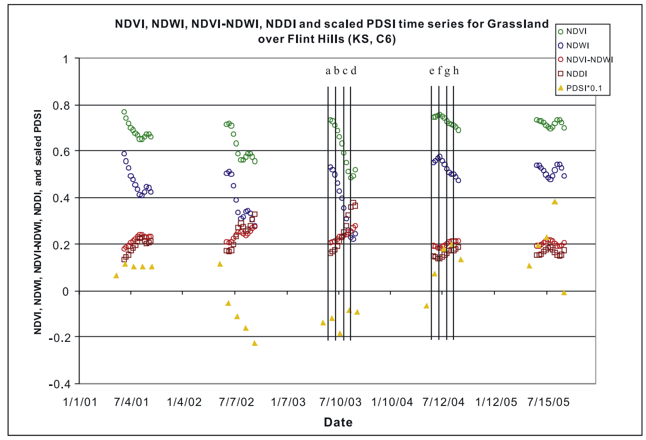

Figure 4. Time series plot of NDVI, NDWI, NDVI-NDWI, NDDI, and PDSI values for climate division 6 of Kansas over the Flint Hills ecoregion (grassland cover type) during the summer (June to September). Time period labels "a–h" refer to the maps of Figure 5.

(a total of 64,137 pixels) over the entire Flint Hills ecoregion. The NDVI and NDWI time series data were averaged for the grassland cover over the Flint Hills, and are plotted in Figure 3. As expected, the NDVI and NDWI values were lower under drought conditions (NDVI = ~0.5 and NDWI = ~0.3) than under non-drought conditions (NDVI>0.6 and NDWI>0.4) during the summer. Because of the variability of drought conditions across the larger area, the relationships between NDVI, NDWI, and drought over the Flint Hills ecoregion were not as pronounced as over the Tallgrass Prairie site. Figure 4 shows summer period time series plots of NDVI, NDWI, NDVI-NDWI difference, NDDI, and scaled (value divided by 10) Palmer Drought Severity Index (PDSI) for the Kansas Climate Division 6 covering the Flint Hills (PDSI data were obtained from the National Climatic Data Center). The PDSI [*Palmer*, 1965] combines temperature and rainfall information to determine the moisture status (dryness or wetness) of the region. Descriptions of the drought categories for PDSI values are listed in Table 1. Results in Figure 4 are consistent with the previous results for the Tallgrass Prairie Preserve with NDVI and NDWI values

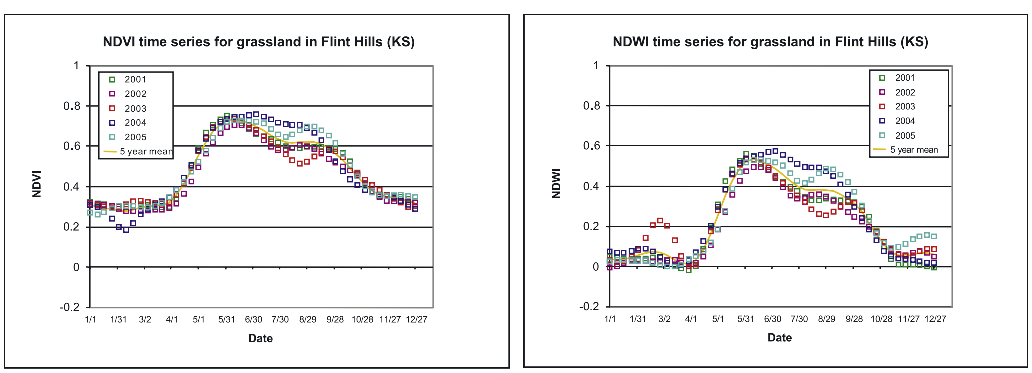

Figure 3. Time series plots of (left) NDVI and (right) NDWI for grassland over Flint Hills ecoregion (averaged value of the random samples extracted from Flint Hills ecoregion grassland cover type).

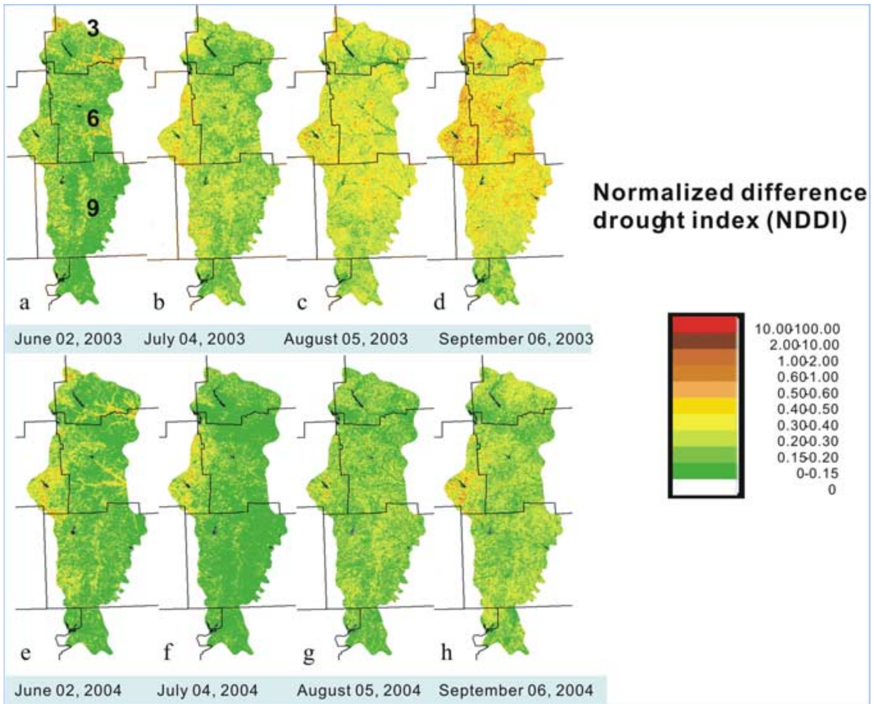

Figure 5. Spatial distribution maps of NDDI over the Flint Hills ecoregion for (a) June 02, 2003; (b) July 04, 2003; (c) August 05, 2003; (d) September 06, 2003; (e) June 02, 2004; (f) July 04, 2004; (g) August 05, 2004; and (h) September 06, 2004. Higher values of the NDDI indicate increasing severity of drought. Climate division numbers of Kansas are labelled in Figure 5a.

decreasing during the summer months of 2002 and 2003. The NDVI-NDWI difference increased only slightly compared to the more pronounced increase of NDDI values during the summer months of these two years, suggesting once again that NDDI may be a more sensitive indicator for drought monitoring.

[12] To illustrate the relationship between NDDI and drought conditions, eight NDDI maps for the Flint Hills ecoregion are shown in Figure 5 (the labels for the different time periods, a–h, are the same as in Figure 4) for a drought (2003) and non-drought (2004) year during the summer months of June to September. Figure 5 shows that NDDI values were much higher for the drought year (2003) than for the non-drought year (2004), particularly for the August 5 and September 6 time periods, which illustrates the potential value of the NDDI for large-area drought monitoring.

5. Conclusions

[13] This initial investigation of a five-year history of MODIS NDVI and NDWI indicates that a strong relationship exists among NDVI, NDWI, and drought conditions over grasslands in the Flint Hills ecoregion of Kansas and Oklahoma. During the summer months, the average NDVI and NDWI values were consistently lower (NDVI < 0.5 and NDWI < 0.3) for the Tallgrass Prairie National Preserve site under drought conditions than under non-drought (normal climate) conditions (NDVI>0.6 and NDWI>0.4). NDWI values decreased more in response to drought conditions than NDVI, indicating that NDWI was more sensitive than NDVI to the onset of drought conditions. The difference between NDVI and NDWI also increased slightly during summer drought conditions. A new vegetation drought index called the NDDI, which combines information from visible, NIR, and SWIR channels was proposed in this study. NDDI values increased during summer drought conditions, which demonstrated that it could be used as an additional indicator for large-area grassland drought monitoring. A more thorough evaluation of the NDDI as a drought monitoring tool for other grassland types (e.g., short and mixed grass prairies), different vegetation types (e.g., crops), and other geographic areas is planned.

[14] **Acknowledgments.** This research was performed under U.S. Geological Survey contract 03CRCN0001. The authors thank James Rowland, Robert Klaver, John Hutchinson, and two anonymous reviewers for their valuable suggestions and comments.

References

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer (1976), A land use and land cover classification system for use with remote sensor data, *U.S. Geol. Surv. Prof. Pap.*, *964*, 28 pp.

Chen, D., and W. Brutsaert (1998), Satellite-sensed distribution and spatial patterns of vegetation parameters over a tallgrass prairie, *J. Atmos. Sci.*, *55*(7), 1225–1238.

Chen, D., J. Huang, and T. J. Jackson (2005), Vegetation water content estimation for corn and soybeans using spectral indices derived from MODIS near- and short-wave infrared bands, *Remote Sens. Environ.*, *98*, 225–236.

Delbart, N., L. Kergoat, T. L. Toan, J. Lhermitte, and G. Picard (2005), Determination of phenological dates in boreal regions using normalized difference water index, *Remote Sens. Environ.*, *97*, 26–38.

Di, L., D. C. Rundquist, and L. Han (1994), Modelling relationships between NDVI and precipitation during vegetative growth cycles, *Int. J. Remote Sens.*, *15*, 2121–2136.

Federal Emergency Management Agency (1995), National mitigation strategy–partnerships for building safer communities, 26 pp., Washington, D. C.

Gao, B. (1996), NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space, *Remote Sens. Environ.*, *58*, 257–266.

Jackson, J. T., D. Chen, M. Cosh, F. Li, M. Anderson, C. Walthall, P. Doriaswamy, and E. R. Hunt (2004), Vegetation water content mapping using Landsat data derived normalized difference water index for corn and soybeans, *Remote Sens. Environ.*, *92*, 475–482.

Ji, L., and A. Peters (2003), Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices, *Remote Sens. Environ.*, *87*, 85–98.

Kogan, F. N. (1991), Observations of the 1990 U.S. drought from the NOAA-11 polar-orbiting satellite, *Drought Network News*, *3*(2), 7–11.

Kogan, F. N. (1995), Droughts of the late 1980s in the United States as derived from NOAA polar orbiting satellite data, *Bull. Am. Meteorol. Soc.*, *76*, 655–668.

Maki, M., M. Ishiara, and M. Tamura (2004), Estimation of leaf water status to monitor the risk of forest fires by using remotely sensed data, *Remote Sens. Environ.*, *90*, 441–450.

McVicar, T. R., and P. N. Bierwirth (2001), Rapidly assessing the 1997 drought in Papua New Guinea using composite AVHRR imagery, *Int. J. Remote Sens.*, *22*, 2109–2128.

Omernik, J. M. (1987), Map supplement: Ecoregions of the conterminous United States, *Ann. Assoc. Am. Geogr.*, *77*(1), 118–125.

Palmer, W. C. (1965), Meteoroogical drought, *Res. Pap. 45*, 58 pp., U. S. Weather Bur., Washington, D. C.

Peters, A. J., E. A. Walter-Shea, J. Lei, A. Vina, M. Hayes, and M. R. Svoboda (2002), Drought monitoring with NDVI-based standardized vegetation index, *Photogramm. Eng. Remote Sens.*, *68*, 71–75.

Reed, B. C. (1993), Using remote sensing and Geographic Information Systems for analyzing landscape/drought interaction, *Int. J. Remote Sens.*, *14*, 3489–3503.

Reed, B. C., J. F. Brown, D. VanderZee, T. R. Loveland, J. W. Merchant, and D. O. Ohlen (1994), Measuring phenological variability from satellite imagery, *J. Vegetation Sci.*, *5*, 703–714.

Rouse, J. W., Jr., H. R. Haas, D. W. Deering, J. A. Schell, and J. C. Harlan (1974), Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation, *NASA/GSFC Type III Final Rep.*, 371 pp., Greenbelt, Md.

Rundquist, B. C., and J. A. Harrington Jr. (2000), The effects of climatic factors on vegetation dynamics of tallgrass and shortgrass cover, *Geocarto Int.*, *15*, 31–36.

Swets, D. L., B. C. Reed, J. R. Rowland, and S. E. Marko (1999), A weighted least-squares approach to temporal smoothing of NDVI, paper presented at ASPRS Annual Conference, Portland, Oreg., 17–21 May.

Tucker, C. J. (1979), Red and photographic infrared linear combinations for monitoring vegetation, *Remote Sens. Environ.*, *8*, 127–150.

Vogelmann, J. E., S. M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and N. Van Driel (2001), Completion of the 1990s national land cover data set for the conterminous United States, *Photogramm. Eng. Remote Sens.*, *67*, 650–662.

Wan, Z., P. Wang, and X. Li (2004), Using MODIS land surface temperature and normalized difference vegetation index for monitoring drought in the southern Great Plains, USA, *Int. J. Remote Sens.*, *25*, 61–72.

Wang, J., K. P. Price, and P. M. Rich (2001), Spatial patterns of NDVI in response to precipitation and temperature in the central Great Plains, *Int. J. Remote Sens.*, *22*, 3827–3844.

Wilhite, D. A. (2000), Preparing for drought: A methodology, in *Drought: A Global Assessment*, *Routledge Hazards Disaster Ser.*, vol. 2, edited by D. A. Wilhite, pp. 89–104, Routledge, Boca Raton, Fla.

Xiao, X., S. Boles, J. Liu, D. Zhuang, and M. Liu (2002), Characterization of forest types in northeastern China, using multi-temporal SPOT-4 VEGETATION sensor data, *Remote Sens. Environ.*, *82*, 335–348.

Yang, L., B. K. Wylie, L. L. Tieszen, and B. C. Reed (1998), An analysis of relationships among climate forcing and time-integrated NDVI of grasslands over the U. S. northern and central Great Plains, *Remote Sens. Environ.*, *65*, 25–37.

J. F. Brown and Y. Gu, SAIC, USGS Center for Earth Resources Observation and Science, 47914 252nd Street, Sioux Falls, SD 57198, USA. (ygu@usgs.gov)

J. P. Verdin, USGS Center for Earth Resources Observation and Science, 47914 252nd Street, Sioux Falls, SD 57198, USA.

B. Wardlow, National Drought Mitigation Center, University of Nebraska at Lincoln, 811 Hardin Hall, 3310 Holdrege Street, Lincoln, NE 68583, USA.