

A PROTOTYPE DROUGHT MONITORING SYSTEM INTEGRATING CLIMATE AND SATELLITE DATA

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ABSTRACT

Droughts are natural hazards with varying patterns in space, time, and intensity. Their dynamic character challenges our ability in planning, predicting, monitoring, and providing relief to affected areas. Because of the spatial and temporal variability and multiple impacts of droughts, we need to improve the tools and data available for mapping and monitoring this phenomenon on all scales. A team of researchers from the US Geological Survey's EROS Data Center, the National Drought Mitigation Center, and the High Plains Regional Climate Center are developing methods for regional-scale mapping and monitoring drought conditions for the conterminous U.S. Currently in its first year, the project is focusing on developing a prototype model for the central U.S. The ultimate goal of the project is to deliver timely geo-referenced information (in the form of maps and data) about areas where the vegetation is impacted by drought, using the Internet as the primary delivery mechanism.

Data collected from the Advanced Very High Resolution Radiometer (AVHRR) sensor provide synoptic, near-real time measurements of surface conditions. Previous studies have established significant relationships between climate variables and satellite-derived vegetation indices over non-irrigated croplands and grasslands. We are researching methods for integrating information provided by satellite-derived metrics on seasonal vegetation performance and climate-based drought indicators to produce a timely and spatially-detailed drought monitoring product. Eventually, this information, coupled with map products of key drought indicators, will be available to many end users for making critical and timely decisions, from farm to regional scale.

BACKGROUND

Droughts are normal recurring climatic phenomena that vary in space, time, and intensity. They may affect people and agriculture at local scales for short periods or cover broad regions or have impacts that are felt for years (for example, The Dust Bowl). The economic effects of drought are significant. It has been estimated that drought results in annual economic losses in the U.S. of between \$6-8 billion (FEMA, 1995). This figure does not include the serious environmental and social costs also associated with drought. Although these losses are substantial, they are difficult to quantify and seem to be increasing as conflicts between sectors increase associated with drought.

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The dynamic nature of droughts causes challenges in planning, predicting, monitoring, and providing relief to drought-stricken areas. Because of the variability and significant multiple impacts of droughts, we need to improve the available tools to capture their spatial and temporal dimensions.

Drought Indicators

There is no universal definition of drought. Definitions have been classified as conceptual and operational. Operational definitions are important because they attempt to determine the onset, severity, spatial extent, and end of drought conditions. Many indicators and indices of drought exist and these may disagree as to the severity of drought conditions. Commonly used drought indices in the U.S. include the Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI), and Standardized Precipitation Index (SPI). Each of these indices has recognized strengths and weaknesses.

Indices are often used to trigger both response and mitigation programs by local, state, and federal government. The PDSI, a meteorological drought index, was the first comprehensive drought index developed in the United States (Palmer, 1965). The PDSI provides a measure of the departure from normal of the moisture supply. The CMI is an indicator of soil moisture in the topsoil. The SPI is a simple calculation solely based on rainfall with a temporal flexibility that is theoretically much better suited to the quicker responses in vegetation detected by satellite imagery. It is a statistical measure on the surplus or lack of precipitation during a given period as a function of the long-term average precipitation (McKee and others, 1993; McKee and others, 1994).

Whereas drought indicators may assimilate information on rainfall, stored soil moisture, or water supply, typically they do not express much local spatial detail (that is, one value may be used to indicate climate conditions over an entire county). Alternatively, drought indices may also be calculated at one location where the input data are collected (that is, a climate station). This information is spatially discrete but only valid for a single location. Thus, a significant drawback of climate-based drought indicators is their lack of spatial detail. In addition, meteorologically-based indices are dependent on data collected at weather stations. Some areas have very sparsely distributed stations and this affects the reliability of the drought indices.

Recently, it has become clear that no one indicator or index is adequate for monitoring drought on a regional scale; instead, a combination of monitoring tools integrated together is preferable for producing regional or national drought maps. An example of this is a drought product called U.S. Drought Monitor, issued weekly as a collaborative effort by the National Drought Mitigation Center (NDMC), National Oceanic and Atmospheric Administration (NOAA), and U.S. Department of Agriculture (see <http://enso.unl.edu/monitor/monitor.html>). This map product provides broad-scale information on where drought is occurring across the United States, but is limited in providing locally-specific drought patterns (Figure 1). For example, a farmer or water resource planner might gain understanding about drought in their region, but detailed geospatial information about specific local conditions would be more useful to them in their planning or mitigation decisions. The integration of satellite-derived information on drought-impacted vegetation with climate-based drought indicators might result in a drought product providing county-level information on drought patterns.

A project recently funded by the U.S. Geological Survey (USGS) is embarking on creating a prototype drought monitoring system by integrating satellite and climate data. The partners in the project are the USGS/EROS Data Center, the NDMC, and the High Plains Regional Climate Center. Currently in its first year, the project is focusing on developing a prototype model for the central US. The goal of the project is to deliver timely geo-referenced information (in the form of maps and geospatial data) about the patterns of drought-impacted vegetation in the lower 48 states of the US, using the Internet as the primary delivery mechanism.

Satellite Metrics

This project draws extensively from two lines of previous research on remote sensing. The first is the application of satellite data to study vegetation phenology, or the seasonal cycle of growth that includes green-up, maturity, senescence, and dormancy. This cycle bears significance in that it exerts control on the exchange of energy and water at the boundary layer. Satellite observations are a valuable source of timely, continuous information that provides spatial detail over large areas for monitoring the phenologic cycle. A second related line of research has demonstrated using satellite data to observe and analyze perturbations in the seasonal cycle of vegetation. In many cases, data from the AVHRR has been the basis for a wide variety of vegetation mapping and monitoring applications as it provides daily global coverage at a nominal 1- km resolution (Loveland, 1991; Tucker and others, 1985; Malingreau, 1986; Defries and others, 1995).

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U.S. Drought Monitor

June 25, 2002
Valid 8 a.m. EDT

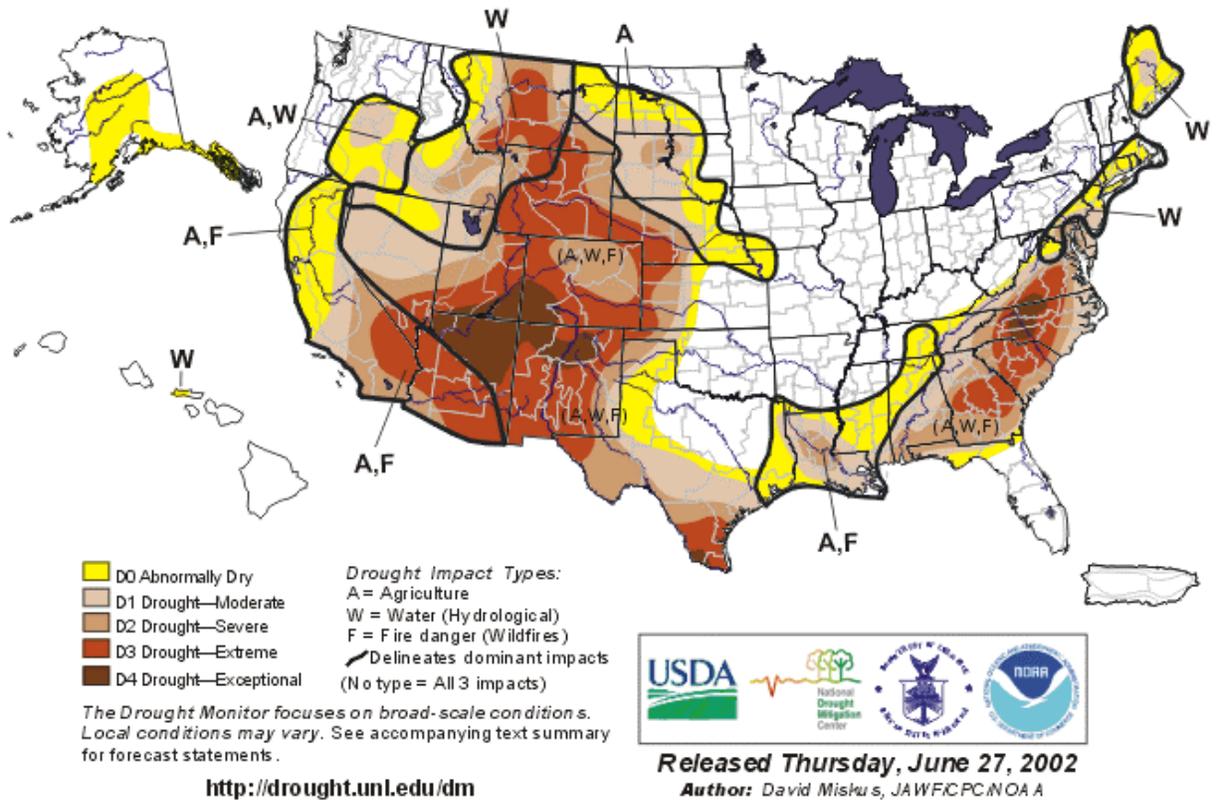


Figure 1. The Drought Monitor map.

The various phenological stages of plant growth are linked to important biotic processes such as net primary production and water balance (Goetz and Prince, 1996; Lechowicz and Koike, 1995; Schwartz, 1992; Running and Nemani, 1991). In addition, lower atmosphere energy and carbon budgets are rapidly modified during the early stages of the growing season. Traditionally, phenology studies have been largely ground-based, with observations mainly providing information concerning specific plants over a limited spatial area. Satellite data analysis, however, provides a means to measure broad scale changes at the ecosystem level by making numerous, repeatable observations. Multi-temporal satellite observations have allowed researchers to quantify seasonal events and to characterize vegetation according to its seasonal patterns (Lloyd, 1990; Loveland and others, 1991; Reed and others, 1993; DeFries and others, 1995; Reed and others, 1996).

Many of the aforementioned studies based their analysis on vegetation indices computed from combinations of visible red and near-infrared spectral measurements collected from satellite-borne sensors. The advantages of using these numerical transforms rather than strictly spectral observations include minimizing soil and other background effects, reducing data dimensionality, providing a degree of standardization for comparison, and enhancing the vegetation signal (Curran, 1981; Malingreau, 1989; Goward, 1989). One of the more commonly used vegetation indices, the normalized difference vegetation index (NDVI), takes advantage of the reflective and absorptive characteristics of plants in the red and near-infrared portions of the electromagnetic spectrum and has been used in research on vegetation yield and productivity. The ability to derive NDVI measurements combined with the frequent temporal coverage and moderate spatial resolution of the AVHRR make this sensor well suited for regional to global scale studies on ecosystem dynamics.

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Environmental factors that appear to cause changes in the phenologic patterns exhibited in satellite data include drought, flood, disease, fire, and human-induced land cover change (such as clearing land for forest harvest or conversion to cropland). Several previous studies have shown the utility of satellite measurements for observing and monitoring drought. For example, Kogan (1991; 1995) has analyzed droughts in the United States using AVHRR data. In this research, he developed several derivations of the NDVI in order to improve the ability to extract drought information from a time-series of satellite composite data. One index, the Vegetation Condition Index (VCI), is a ratio of the NDVI collected in a given period compared to its historical range (maximum minus minimum) derived over several years of record. Possible VCI values range from 1 to 100. Kogan (1995) stated that VCI values of 35 and under indicate drought.

Building on this research, Kogan and others (Liu and Kogan, 1996; Kogan, 1997; Unganai and Kogan, 1998) have demonstrated the utility of the VCI in Africa, South America, and Asia. They also have developed an index that utilized the thermal data from AVHRR channel 4 known as the Temperature Condition Index (TCI). The satellite index data are compared to other measures, such as precipitation, atmospheric anomaly fields, and agricultural crop yield for validation purposes. The authors were able to predict corn yields from 6 to 13 weeks prior to harvest with reasonable accuracy by applying the VCI and TCI data. These studies were conducted at a spatial resolution of 16 km² based on NOAA Global Vegetation Index product.

Viau (2000) and others have compared the previously mentioned VCI and the NDVI (extracted from AVHRR data) to measurements of the SPI over less than 20 weather stations in Spain. The authors were very encouraged by their results, but since so few sites were used, the results were not statistically significant. In addition, Peters and others (2002) developed a Standardized Vegetation Index (SVI) for the central United States based on 1-km² resolution AVHRR data and covers the period 1989 through the present.

Several studies have investigated relationships between satellite-derived metrics and climate variables. In a recent study based in the Great Plains, Budde and Reed (written communication) demonstrated the relationships between NDVI-based seasonal metrics and climate variables for 68 stations in the central United States. Using a stepwise linear regression approach, the authors demonstrated that variables associated with moisture availability and thermal conditions were found to exert control on the performance of both grassland and cropland areas. Another study (Yang and others, 1998) shows moderate to strong relationships ($R^2 = 0.39-0.94$) between annual integrated NDVI and several precipitation measures for specific grassland classes in the U.S. The authors suggest an integrated approach involving numerical models, remote sensing, and field observations to monitor grassland dynamics.

This drought monitoring work builds on the aforementioned research, and is complementary to those studies not based on seasonal metrics. We plan to model the relationships between meteorological drought indicators and satellite-derived metrics. The satellite-derived metrics will add improved spatial detail that is currently not a feature of many drought indicators and will also indicate where the drought is impacting the surface vegetation.

METHODS

Satellite Data

Since 1989, the USGS/EROS Data Center (EDC) has assembled and processed multi-year AVHRR greenness composite data for the conterminous U.S. (Eidenshink, 1992). In 2001, the EDC produced greenness products incorporating improved atmospheric correction for the effects of water vapor, ozone, and Rayleigh scattering (Eidenshink, written communication). These satellite images provide the basis for a series of metrics based on the NDVI, such as the start of the growing season, the end of the growing season, the time of peak growth, and seasonal integrated greenness. These metrics describe vegetation dynamics and make it possible to extract information pertinent to monitoring surface phenomena (Reed and Yang, 1997). We have produced a database for 1989 to 2001 for the conterminous U.S. that includes smoothed NDVI data and many seasonal metrics. This data are available to users at the EDC anonymous ftp site.

NDVI data are often affected by a number of phenomena including cloud contamination, atmospheric perturbations, and variable illumination and viewing geometry, all of which usually reduce the NDVI value (Los and others, 1994). We developed a weighted least squares linear regression approach to smooth the multi-temporal NDVI signal to reduce this contamination. This approach uses a moving window of five temporal periods for calculating a regression line. The window is moved one period at a time, resulting in a family of regression lines for each point; this family of lines is then averaged. Since the factors that cause contamination usually reduce NDVI values, the technique also incorporates a weighting factor that favors peak points over points with low values. A

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final operation assures that all desired peak NDVI values are retained. These steps result in a smoothed NDVI data series that minimizes noise that might be misinterpreted as significant phenological events. Figure 2 shows the results of smoothing over one AVHRR pixel.

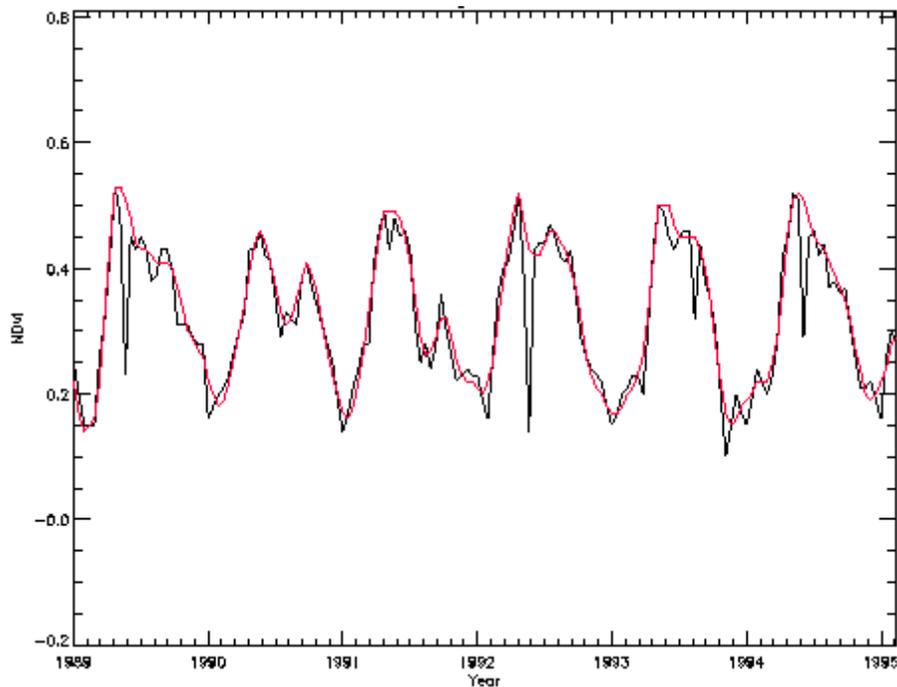


Figure 2. Raw and smooth 14-day NDVI for one pixel. The smooth NDVI data are graphed in red.

To derive seasonal metrics from the smoothed NDVI we analyze temporal curve characteristics rather than absolute NDVI values on a pixel-by-pixel basis. This is significant because the satellite series covering our period of study (1989 – 2001) includes data collected from three NOAA satellites. Because of orbital decay over the life spans of these satellites, basing metrics on curve characteristics improves the robustness of intra-satellite comparisons. To identify the start of season, we locate a well-defined trend change in NDVI values using a backward looking moving average (Reed and others, 1993). Using this method, we calculate an average within a window (for example, 5 observations) and compare it to the current (smoothed) observation that is the last in the series. We then proceed to the next observation and repeat the process. When the observed value becomes greater than the moving average, a trend change has been established; we label this the start of season. The end of season is identified in a similar manner, except the moving average is run in the opposite direction. Time integrated NDVI is calculated as the area under the NDVI curve between the start and end of the growing season. Figure 3 shows several of these metrics on a stylized NDVI curve.

There are considerable difficulties in using time series NDVI data to identify a key phenology measure, the start of the growing season. Past efforts have included assigning a threshold NDVI value (e.g., 0.099; Lloyd, 1990) at which vegetative activity is assumed to begin. This threshold, however, varies with vegetation type, soil background, and illumination conditions. In fact, our research has shown that the NDVI value at the start of the growing season ranges from 0.06 to over 0.20. Therefore, it is not possible to establish a single, meaningful threshold to signify the onset (or end) of vegetative activity for the wide variety of cover types that exist.

Our method uses a different approach, as we calculate phenological metrics based on temporal NDVI curve characteristics, rather than the often noisy actual NDVI values. In addition to being based on a well-defined trend change in the NDVI (and vegetation vigor), we believe that this approach allows more consistent comparisons of data from sensors aboard the NOAA satellite series as well as new sensors such as MODIS and SPOT Vegetation.

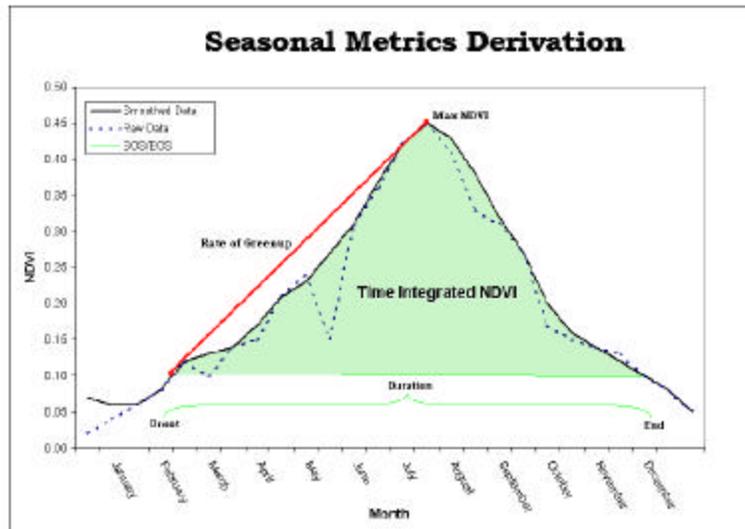


Figure 3. Suite of phenologic metrics calculated from satellite data.

For this study, we calculate a seasonal greenness (SG) product that is updated every two weeks based on the 14-day NDVI composites distributed by the EDC. SG is calculated as a daily integration of the NDVI curve between the start of season and the current date (Figure 4).

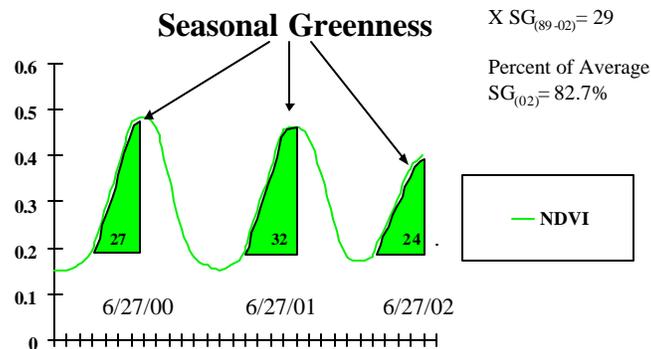


Figure 4. Calculation of the Seasonal Greenness metric.

For vegetation monitoring, the SG metric for the any period is compared to the mean of the same time period from the historical (from 1989 to current year) database. The measure is expressed as a percentage by the formula:

$$\text{Percent of Average SG} = (\text{current SG} / \text{mean SG}) * 100$$

Areas that are above and below the mean SG are highlighted by this calculation. Areas below the mean may result from a variety of influences including standing water, drought, deforestation, or urbanization (see Figure 5).

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We have done some initial testing of the statistical relationships between the SG (percent of average) and more traditional climate indices (e.g., PDSI) using the southeast U.S. as a test case (Brown and Reed, 2001). Preliminary results showed different vegetation types indicate differing responses to drought conditions. This test case provided motivation to pursue the prototype effort that is described here.

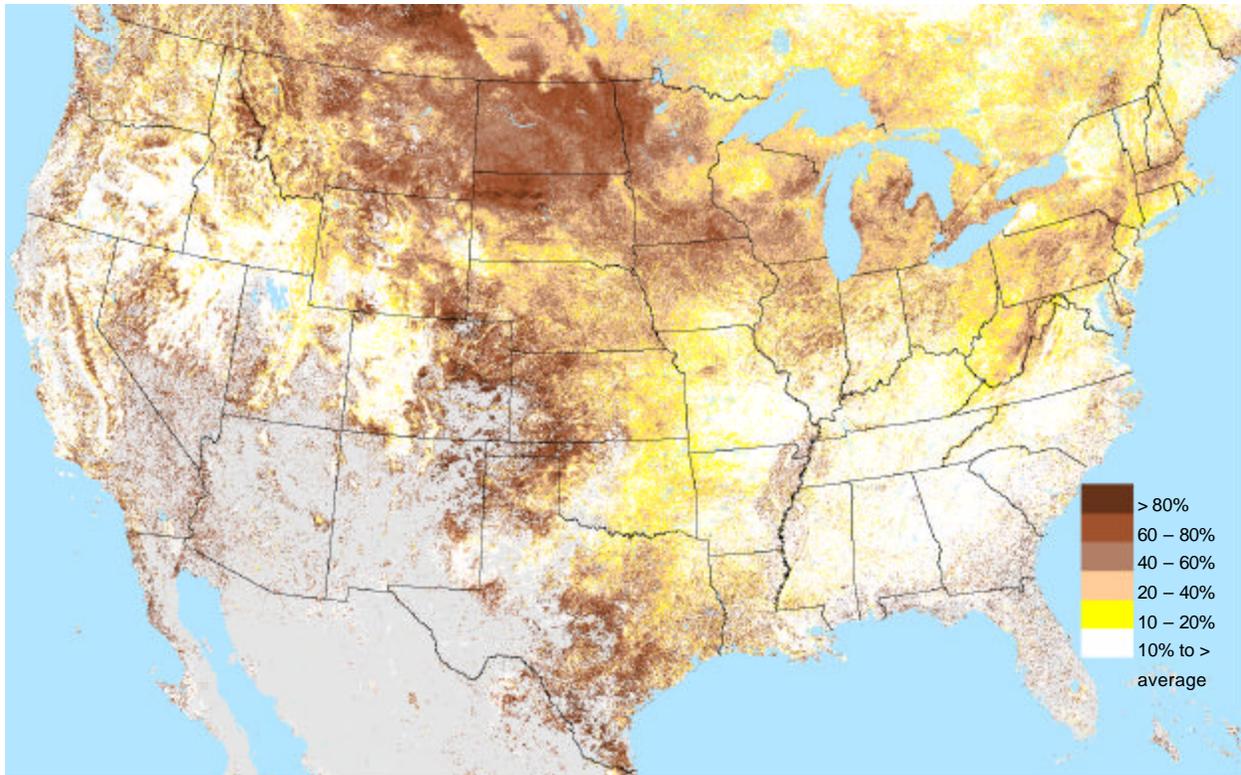


Figure 5. Percent of Average SG for June 27, 2002 (Colored classes show below average SG).

Climate Data

Because many factors can lead to below average SG, we are testing methods to best identify the areas where below average SG are caused by drought. Because these environmental patterns will also be influenced by factors such as elevation, land cover, and land management, those data will be included in the analysis where available. For the pilot study, we are retrieving and analyzing meteorological variables and drought indices for weather stations in the central U.S. using the Unified Climate Access Network (UCAN) as implemented at the High Plains Regional Climate Center (HPRCC). Variables like air temperature, humidity, solar radiation, wind speed, and precipitation effect the rate of evapotranspiration and in turn determine whether soil moisture is sufficient for vigorous growth and development of plants. These variables are available for both the HPRCC Regional Network and in the NOAA TD3200 data sets in the UCAN system. The pilot study will thus use meteorological data as input to drought indices like the PDSI and the SPI. Our analysis will focus on determining which variables correlate best with the SG data and at what time scales.

Modeling Satellite Data and Climate Data

We need tools to explore and describe relatively complex patterns and processes related to drought impacts. Data mining tools such as decision tree analysis can provide flexible and robust analytical methods for determining the relationships between complex environmental data (De'ath and Fabricius, 2000). We are using decision tree methods as well as more traditional multiple regression techniques, in order to develop the models for the relationships between the satellite metric data and the climate data (including the drought indices). We anticipate having preliminary model results in the fall and winter of 2002.

Our objective is to use the model results to produce spatially-detailed georeferenced digital maps of drought-impacted vegetation. Once the models are developed, we will then extrapolate from the weather station locations to

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the pilot study area. We will incorporate the satellite-based information (current SG and the percent of average SG) combined with traditional meteorological drought indicators to develop a near-real time Drought Impacts Index (DII) that is spatially continuous at a resolution of 1-km. This product have a numerical scale (as yet to be determined) where levels of drought impacts on vegetation will be distinguished. Calculation and production of the DII spatial product will most likely incorporate rule-based models extracted from the decision tree analysis.

APPLICATIONS

We plan to distribute the SG, percent of average SG, and the DII data sets as map graphics and as geospatial image files to interested users via the Internet and anonymous FTP. As these are new products, applications will become apparent as the project advances. The Drought Monitor has an established user community that includes users on federal, state, and on an individual level. We plan on distributing map graphics of the SG, percent of average SG, and the DII, for evaluation by these users from the NDMC web site. We anticipate receiving constructive criticism and suggestions by using this venue for distribution.

The LANDFIRE project, a joint effort between the U.S. Forest Service and Department of Interior agencies plans to test and evaluate the DII for estimating wildfire danger. Recent SG and percent of average SG will soon be available for viewing at the USGS Integrated Vegetation Mapping home page (<http://gisdata.usgs.net/website/ivm/>). This mapping page is designed to provide interactive map view using near real time satellite vegetation data combined with other USGS data layers such as elevation, populated placed, roads, and streams.

SUMMARY

The prototype drought monitoring project has been funded as a three year project and is just underway. We are now beginning to collect the necessary climate data for the research, and results of the modeling will be available in the near future. We have completed processing a database of SG for the historical NDVI archive for the lower 48 states using the EDC water vapor corrected NDVI (1989 – 2001). During the growing season of 2002, near real time processing of the SG and the percent of average SG has been underway since the end of May, 2002. As we produce model results, and create new digital maps and graphics, we will make these available to users via the USGS Integrated Vegetation Mapping and the Drought Monitor home pages.

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REFERENCES

- Brown, J.F., and Reed, B.C. (2001). Monitoring regional drought with satellite data. The Association of American Geographers, 97th Annual Meeting, New York City, NY. (abstract).
- Budde, M. and Reed, B.C. (no date). A comparison of satellite derived vegetation metrics and climate variables in the central United States. *Remote Sensing of Environment*, in review.
- Curran, P. J. (1981). Multispectral remote sensing for estimating biomass and productivity. In: *Plants and the Daylight Spectrum*, H. Smith (ed.), London, Academic Press, pp. 65-99.
- De'ath, Glenn, and Fabricius, K.E. (2000). Classification and regression trees—a powerful yet simple technique for ecological data analysis. *Ecology*. 81(11):3178-3192.
- DeFries, R., M. Hansen, and J. Townshend (1995). Global discrimination of land cover types from metrics derived from AVHRR Pathfinder data. *Remote Sensing of Environment*. 54:209-222.
- Eidenshink, J.C. (1992). The 1990 conterminous U.S. AVHRR data set. *Photogrammetric Engineering & Remote Sensing*. 58:809-813.

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- Federal Emergency Management Agency (1995). National mitigation strategy—partnerships for building safer communities: Washington, D.C., 26 pp.
- Goetz, S.J. and S.D. Prince (1996). Remote sensing of net primary production in boreal forest stand. *Agricultural and Forest Meteorology*, 78:149-179.
- Goward, S. N. (1989). Satellite bioclimatology. *Journal of Climate*, 2:710-720.
- Goward, S. N., Tucker, C. J., and Dye, D. G. (1985). North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. *Vegetatio*, 64:3-14.
- Justice, C. O., Townshend, J.R.G., Holben, B.N., and Tucker, C.J. (1985). Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing*, 6:1271-1318.
- Kogan, F.N. (1995). Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorological Society*, 76(5):655-668.
- Kogan, F.N. (1997). Global drought watch from space. *Bulletin of the American Meteorological Society*, 78(4):621-636.
- Kogan, F.N. (1998). Global drought and flood-watch from NOAA polar-orbiting satellites. *Advances in Space Research*, 21(3):477-480.
- Lechowicz, M.J. and Koike, T. (1995). Phenology and seasonality of woody plants—an unappreciated element in global change research? *Canadian Journal of Botany*, 73:147-148.
- Liu, W.T., and Kogan, F.N. (1996). Monitoring regional drought using the vegetation condition index. *International Journal of Remote Sensing*, 17(14):2761-2782.
- Lloyd, D. (1990). A phenological classification of terrestrial vegetation cover using shortwave vegetation index imagery. *International Journal of Remote Sensing*, 11:2269-2279.
- Los, S.O., Justice, C.O., and Tucker, C.J. (1994). A global 1 by 1 NDVI data set for climate studies derived from the GIMMS continental NDVI data. *International Journal of Remote Sensing*, 15(17):3493-3518.
- Loveland, T.R., Merchant, J.W., Ohlen, D.O., and Brown, J.F. (1991). Development of a land cover characteristics data base for the conterminous U.S. *Photogrammetric Engineering & Remote Sensing*, 57(11):1453-1463.
- Loveland, T.R., Merchant, J.W., Ohlen, D.O., Brown, J.F., Reed, B.C., and Steyaert, L.T. (1993). Conterminous U.S. Land Cover Characteristics Data Set: 1990 Prototype, EROS Data Center, U.S. Geological Survey CD-ROM [includes Readme file.]
- Malingreau, J. P. (1986). Global vegetation dynamics: satellite observations over Asia. *International Journal of Remote Sensing*, 7:1121-1146.
- Malingreau, J. P. (1989). The vegetation index and the study of vegetation dynamics. In: *Application of Remote Sensing to Agrometeorology*. F. Toselli (ed.), ECSC, Brussels and Luxembourg, pp. 285-303.
- McKee, T. B., Doesken, N. J., and Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *Preprints, 8th Conf. on Applied Climatology*, Anaheim, CA, Amer. Meteor. Soc., pp. 179-184.
- McKee, T. B., Doesken, N. J., and Kleist, J. (1994). Drought monitoring with multiple time scales. *Preprints, 9th Conf. On Applied Climatology*, Dallas, TX, Amer. Meteor. Soc., pp. 233-236.
- Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., and Nemani, R.R. (1997). Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature*, 386:695-702.
- Palmer, W. C. (1965). Meteorological drought. U.S. Department of Commerce Weather Bureau Research Paper No. 45, 58 pp.
- Peters, A.J., Walter-Shea, E.A., Lei, J., Vina, A., Hayes, M., Svoboda, M.R. (2002). Drought monitoring with NDVI-based standardized vegetation index. *Photogrammetric Engineering & Remote Sensing*, 68(1):71-75.
- Reed, B.C., Brown, J.F., VanderZee, D., Loveland, T.R., Merchant, J.W., and Ohlen, D.O. (1994). Measuring phenological variability from satellite imagery. *Journal of Vegetation Science*, 5:703-714.
- Reed, B.C., Loveland, T.R., and Tieszen, L.L. (1996). An approach for using AVHRR data to monitor U.S. Great Plains grasslands. *Geocarto International*, 11(3):13-22.
- Reed, B.C. and Yang, L. (1997). Seasonal vegetation characteristics of the United States. *Geocarto International*, 12(2):65-71.
- Running, S.W. and Nemani, R.R. (1991). Regional hydrologic and carbon balance responses of forests resulting from potential climate change. *Climate Change*, 19:349-368.
- Seiler, R.A., Kogan, F., and Sullivan, J. (1998). AVHRR-based vegetation and temperature condition indices for drought detection in Argentina. *Advances in Space Research*, 21(3):481-484.
- Schwartz, M.D. (1992). Phenology and springtime surface layer change. *Monthly Weather Review*, 120:2570-2578.
- Townshend, J.R.G., Justice, C.O., and Kalb, V. (1987). Characterization and classification of South American land cover types using satellite data. *International Journal of Remote Sensing*, 8:127-150.
- Tucker, C.J., Townshend, J.R.G., and Goff, T.E. (1985). African land cover classification using satellite data.

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Science, 9227(4685):369-375.

Unganai, L.S., and Kogan, F.N. (1998). Drought monitoring and corn yield estimation in southern Africa from AVHRR data. *Remote Sensing of the Environment*, 63:219-232.

Viau, A.A., Vogt, J.V., and Beudin, I. (2000). Comparison of a satellite-based and a precipitation-based drought index. *Canadian Journal of Remote Sensing*, 26(6):580-583.

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

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