The Vegetation Drought Response Index (VegDRI): A New Drought Monitoring Approach for Vegetation

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1. Introduction

Remote sensing has proven useful for large-area vegetation monitoring given the synoptic coverage, high temporal repeat cycle, and continuous, moderate resolution observations of satellite-based sensors. In particular, time-series normalized difference vegetation index (NDVI) data from the global imager, the Advanced Very High Resolution Radiometer (AVHRR), has been widely used for vegetation and ecosystem monitoring (Tucker et al., 1985; Reed et al., 1994; Jakubauskas et al., 2002). Analysis of time-series NDVI data and NDVI-derived metrics have been an effective means for identifying vegetation condition anomalies (e.g., apparent declines in vegetation health). Operational efforts such as the Green Report (http://www.kars.ku.edu/products/greenreport.shtml), RangeView (http://rangeview.arizona.edu/), and the U.S. Forest Service's Wildland Fire Assessment System (http://www.wfas.net/content/view/30/47/) provide NDVI-derived products that describe the percentage or deviation of current vegetation conditions from the normal conditions expressed historically in the NDVI data. The Vegetation Condition Index (VCI) (Kogan, 1990), which is based on a transformation of the AVHRR NDVI data, and the Temperature Condition Index (TCI), which is calculated from AVHRR's thermal data (Kogan, 1995), are operationally produced and have been commonly used for national- to global-scale drought monitoring (Liu and Kogan, 1996; Kogan, 1997; Unganai and Kogan, 1998). Although these numerous operational products have been useful for vegetation monitoring, they are limited for effectively characterizing the impact of drought on vegetation because the anomalies caused by drought stress cannot be discriminated from anomalies produced by other environmental causes of vegetation stress (e.g., flooding, fire, pest infestation, and hail damage) and anthropogenic drivers (e.g., land cover/land use conversion). Additional information is required to discriminate the drought-impacted areas from locations where the vegetation is being influenced by these other environmental and anthropogenic factors.

Traditionally, climate-based drought indicators such as the Palmer Drought Severity Index (PDSI) and Standardized Precipitation Index (SPI) have been used for drought monitoring. However, climate-based drought monitoring approaches have a limited spatial precision at which drought patterns can be mapped because the indices are calculated from point-based meteorological measurements collected at weather station locations. In addition, weather stations are scarce in remote areas and not uniformly distributed. As a result, climate-based drought index maps depict broad-scale drought patterns that are produced from point-based data using statistical-based spatial interpolation techniques, and the level of spatial detail in those patterns is highly dependent on the density and distribution of weather stations. Therefore, the spatial detail in climate-based drought index maps is limited due to the dependence on uneven and sparse weather station distributions, which limits drought planning and monitoring activities in areas not well covered by weather stations.

The Vegetation Drought Response Index (VegDRI) is a new drought monitoring tool that integrates satellite-based NDVI observations, climate-based drought index data, and several biophysical characteristics of the environment to produce an indicator that expresses the level of drought stress on vegetation. VegDRI integrates concepts from both the remote sensing-based NDVI and the climate-based drought index approaches to produce 1-km resolution maps that characterize the intensity and spatial pattern of drought-induced vegetation stress over large areas. In the VegDRI approach, the 1-km NDVI images provide detailed spatial patterns of vegetation conditions, which are analyzed in combination with dryness information represented in the climate-based drought index data to identify and characterize the intensity and spatial extent of drought conditions. Biophysical parameters such as the

land cover type, soil available water holding capacity, irrigation status, and ecological setting of an area are also analyzed because these environmental characteristics can influence specific climate-vegetation interactions. VegDRI was developed in a collaborative research effort between the National Drought Mitigation Center (NDMC) and USGS Earth Resources Observation and Science (EROS) Center and is designed to be a near-real time, national drought monitoring tool for the conterminous United States. The 1-km VegDRI maps depict more spatially detailed, drought-specific information related to vegetation than traditional drought monitoring tools. In addition, this information is provided on relevant spatial and temporal scales to decision makers working at the local to national level.

2. VegDRI Methodology and Data Inputs

2.1 Overview of VegDRI

VegDRI characterizes the level of drought stress on vegetation by integrating two satellite-based NDVI metrics, two climate-based drought indices, and five biophysical characteristics of the environment (listed in Table 1 and discussed in Section 2.2). The VegDRI methodology consists of three main steps:

1) processing, summarization, and organization of the data for each input variable into a database (Section 2.3),
2) development of empirically derived VegDRI models for three seasonal phases (spring, summer, and fall) (Table 2) by applying a classification and regression tree (CART) analysis technique to the historical information in the database (Section 2.4), and
3) application of the seasonal models to geospatial data to produce a 1-km VegDRI map (Section 2.5).

VegDRI maps (Figure 1) are currently produced over a 15-state region of the central United States in an operational, near-real time fashion. VegDRI contains seven categories reflecting varying levels of drought-induced vegetation stress that are based on the PDSI classification scheme (Palmer, 1965). The maps also include three additional classes that depict areas over which VegDRI values cannot be calculated. These additional classes include water, out of season (i.e., time when the vegetation is not photosynthetically active for a location), and no season (i.e., locations such as the southwestern United States where no detectable vegetation response was detected in the historical AVHRR NDVI data).

2.2 VegDRI Data Inputs

2.2.1 *Satellite-Based NDVI-Related Variables*

A 17-year time series (1989 – 2005) of biweekly composited, 1-km AVHRR NDVI data (Eidenshink, 2006) was used to calculate the two vegetation-related metrics, percent average seasonal greenness (PASG), and start of season anomaly (SOSA) for inclusion into the VegDRI model. Prior to the calculation of these metrics, a weighted least squares regression technique (Swets et al., 1999) was applied to the NDVI time series to minimize non-vegetation-related noise and other artifacts (e.g., clouds and variable illumination and viewing angles) that are commonly found in the 14-day NDVI composites (Los et al., 1994).

- ***PASG*** is a biweekly measure that reflects how the vegetation conditions for a specific period during the growing season compare to historical average conditions for that same period over the 17-year AVHRR historical record. PASG is calculated in four steps: 1) the historical median start (SOST) and end of season (EOST) was identified for each pixel using a delayed or moving window averaging technique (Reed et al., 1994); 2) the seasonal greenness (SG) (i.e., NDVI value accumulated from the SOST up to the current biweekly period in the growing season) was calculated for each biweekly period until the EOST was reached (see Brown et al. (in press) for more details about the SG calculations); 3) period-specific mean SG values were then calculated from the SG values of the individual years; and 4) for each year, the period-specific SG value at the pixel level was divided by mean SG for that period to produce the historical time series of PASG values.

- ***SOSA:*** The SOSA metric represents the departure of the SOST day of year (DOY) from the historical median SOST DOY for each pixel and was included in the VegDRI model to account for the different timings of emergence of various natural and agricultural vegetation types as well as land cover change, all of which can influence the seasonal vegetation performance (and thus PASG) recorded in the satellite observations. The SOSA also allows a key distinction to be made between areas having a low early season PASG due to environmental-related vegetation stress versus non-environmental related factors such as crop rotations or other land cover changes that are unrelated to drought stress. The SOSA was calculated at the pixel level for each year in the period of record by subtracting the SOST DOY for a specific year from the median SOST DOY over the 17-year period.

2.2.2 *Climate-Based Drought Index Variables*

Two climate-based drought indices, the Standardized Precipitation Index (SPI) and the self-calibrated Palmer Drought Severity Index (PDSI), were incorporated into the VegDRI model. A 17-year time series of data for both indices was generated for specific weather station locations from the National Agricultural Decision Support System (NADSS). The indices' values were calculated on the same biweekly time-step to be consistent with the compositing period length of the AVHRR NDVI data. Rigorous quality control was applied during weather station selection to retain only weather stations that were currently active, had a sufficient historical record length (e.g., minimum of 30 years of precipitation data), contained minimal missing data (e.g., less than 10 percent of all observations missing), and were not located in urban areas or adjacent to large water bodies.

- ***SPI:*** The SPI is designed to quantify the precipitation anomaly for a specific time period (e.g., previous 1, 3, 5, or 12 months) based on the long-term precipitation record over that same time period (McKee et al., 1995). The SPI is calculated by fitting the long-term precipitation record over a specific time step to a probability distribution, which is then transformed to a gamma distribution. Then, the mean SPI for a specific location and time period is set to zero. The positive and negative SPI values represent more and less precipitation compared to historical mean precipitation, respectively (Edwards and McKee, 1997). The SPI was used as a measure of dryness in VegDRI and a single SPI interval was selected for each seasonal VegDRI model based on statistical testing of SPI intervals ranging from 1 to 52 weeks. A 52-week SPI was found to provide the best predictive VegDRI accuracy for the spring and summer models, and a 40-week SPI performed best for the fall model.

- ***PDSI:*** A self-calibrated PDSI (Wells et al., 2004), which reflects how soil moisture conditions compare to normal conditions using a supply-and-demand model of a water balance equation, was selected as the dependent variable for the VegDRI model. This index was an appropriate dependent variable for VegDRI because the PDSI accounts for the effects of precipitation and temperature, both of which strongly influence the drought stress on vegetation. In addition, the PDSI is a well-recognized drought metric and the PDSI-like drought scale implemented for VegDRI is familiar to the drought community.

2.2.3 *Static Biophysical Variables*

Several static biophysical variables describing various environmental characteristics that influence drought stress on vegetation were integrated into VegDRI:

- ***Land Cover Type (LC):*** A 1-km land cover map was generated from the 30-m USGS National Land Cover Dataset (NLCD 2001) (Homer et al., 2004) using a zonal majority function. A land cover component was included to better parameterize the VegDRI model to different NDVI signals and climate-vegetation responses exhibited by different land cover types.

- ***Soil available water capacity (AWC):*** AWC was extracted from the STATSGO database for each STATSGO soil map unit (USDA, 1994), which was then converted to a 1-km grid. The AWC variable was used to represent the variability among soils to hold moisture and make it available to plants.

- ***Ecoregion Type (ECO):*** A 1-km ecoregion grid based on the Omernik Level III ecoregion data (Omernik, 1987) was used to provide a geographic framework that accounts for the considerable abiotic (e.g., climate, geology, elevation, and hydrology) and biotic (e.g., plant characteristics) variability exhibited across the United States, which can influence basic climate conditions and the level of drought stress on vegetation.

- ***Percent Irrigated Agriculture (IrrAg):*** A 1-km percent irrigated agriculture map was derived from a 250-m irrigated lands map based on three data sources: satellite-derived vegetation index (VI) data, USDA county-level irrigation summary statistics for 2002, and general land cover information. The satellite data, collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Earth Observing System Terra platform (Justice and Townshend, 2002), provided a source for a measurement of the annual peak of growing season productivity at a 250-m spatial resolution. The peak VI was calculated for 2002 for the derivation of irrigated areas. In an automated classification environment (ArcView Avenue), the 2002 county statistics (i.e,, number of irrigated acres) provided the criteria for dynamically identifying and selecting the number of cells with the highest annual peak MODIS VI within the appropriate land cover categories. The land cover information, provided by the 2001 National Land Cover Database (Homer et al., 2004), guided the model so that land cover categories other than pasture/hay or cultivated crops were eliminated from consideration. Discrimination between irrigated and non-irrigated areas is essential in the VegDRI models because rainfed vegetation has greater sensitivity and response to drought than vegetation receiving targeted water applications.

- ***Elevation (ELEV):*** A 1-km digital elevation grid extracted from GTOPO30 (Gesch et al., 1999) was included to distinguish elevational differences for a specific land cover and/or soil type in the VegDRI model, which can result in differing levels of sensitivity to drought stress among locations with similar land cover and/or soils.

2.3 Database Development

A database of the satellite, climate, and biophysical data discussed above was assembled for 1,342 weather station locations over 15 states (note: an additional 564 stations will be added for the western expansion in 2008) for VegDRI model development. Biweekly historical SPI and self-calibrated PDSI data were calculated and sequentially ordered for each station. For the variables that were in a gridded format, summary statistics were calculated for a 3-by-3 pixel window centered on each station location. The average value for continuous variables (e.g., mean AWC) and the dominant (or majority) class for the categorical variables (e.g., majority land cover type) were calculated from within the window and added to the database for each station. Biweekly historical PASG values were temporally stacked in the same manner as the climate data, and a single SOSA value per year was used for each station. A single, constant value was used for each of the static biophysical records across the 17 years in the database. The records in the database were then subdivided into the three seasonal phases (Table 2) for which VegDRI models were developed.

2.4 Model Generation and Implementation

A commercial CART algorithm called Cubist (Rulequest, 2007) was used to analyze the historical data and generate three seasonal, rule-based piecewise linear regression models (note: rules and instances options were used). The rule sets from the appropriate seasonal Cubist model were then applied to the gridded image input data using MapCubist software, which was developed at the USGS EROS Center, to produce the 1-km VegDRI maps. For the SPI, which was acquired as point-based data for individual weather stations, 1-km grids had to be generated for the biweekly periods using an inverse distance weighting interpolation approach. For near-real time, operational VegDRI map production, the climate-based indices and the NDVI-derived metrics are updated for the previous two-week period and the appropriate seasonal model is applied to this information along with the static biophysical variables to generate a new VegDRI map within 24 hours of the last data acquisition. Further information about the specific inputs and methods for the VegDRI discussed in Section 2 is provided in Brown et al. (in press).

3. Results and Products

The 1-km resolution of the VegDRI maps allows more detailed spatial patterns and local variability in drought conditions to be mapped and monitored than the current state-of-the-art drought monitoring tool, the U.S. Drought Monitor (USDM), as shown in the July 2007 example for Nebraska (Figure 2). The USDM and VegDRI maps both characterize similar, broad-scale drought patterns across Nebraska, but the VegDRI map depicts considerably more substate to subcounty variations in the drought conditions. This result is best demonstrated in the panhandle region of western Nebraska, where the USDM classifies several counties into a single drought category while VegDRI detects areas with differing levels of drought severity within each county.

VegDRI maps have been operationally produced and updated on a biweekly cycle during the growing season (May – October) for a 15-state region of the central United States for 2006 and 2007 (Figure 3). Geographic expansion of VegDRI across the western United States is planned for the spring of 2008 and complete coverage of the conterminous United States is targeted for 2009. Table 3 summarizes the VegDRI product characteristics. Work is also currently under way to improve the temporal resolution of the VegDRI by moving to weekly updates of the maps. In addition, the development of a retrospective time series of VegDRI maps dating back to 1989 for the conterminous United States is scheduled.

VegDRI maps and summary information can be accessed by the general public via the World Wide Web from two locations.

- ***Drought Monitoring viewer*** (http://gisdata.usgs.net/website/Drought_Monitoring/viewer.php), hosted by the USGS, provides an interactive environment where the VegDRI maps can be viewed in combination with a variety of geospatial information layers (e.g., political boundaries, roads, hydrography, land cover, NDVI-derived metrics, and gridded precipitation products).
- ***VegDRI Web page*** (http://www.drought.unl.edu/vegdri/VegDRI_Main.htm), hosted by the NDMC, provides a series of quick view VegDRI maps (at multiple spatial scales and for specific land cover types) and accompanying drought area statistics tables. Change maps, time-series animations of VegDRI maps, and a historical archive of VegDRI are also available.

Currently, VegDRI data are not available for download to the general public. The data will be made available for distribution once the evaluation of VegDRI's accuracy is completed and the index's strengths and weaknesses can be characterized. In 2009, we plan to distribute VegDRI data in a GIS-ready format (GeoTiff) projected in the Lambert Azimuthal Equal Area projection.

VegDRI evaluation results have been promising and suggest this new index holds considerable potential for large-area drought monitoring. To date, three types of evaluation have been conducted.

1) *K-fold cross-validation (using holdout years)*: A 17-fold cross-validation (Kohavi, 1995) for each seasonal model revealed a relative high predictive accuracy indicated by the mean correlation coefficient (r ±1 standard deviation) of the model-predicted VegDRI versus the observed VegDRI across each of 17 models tested based on a different holdout year. The cross-validation results are r = 0.81±0.02, 0.86±0.01, 0.88±0.01 for the spring, summer, and fall VegDRI models, respectively. For further information on the results of the cross-validation, see Brown et al. (in press).
2) *Spatial pattern analysis*: The VegDRI maps were compared with other commonly used drought index maps such as the USDM to determine the level of spatial agreement between their broad-scale drought condition patterns. Although this approach is qualitative, the comparison with an independent data source such as the USDM allows the relative accuracy of the VegDRI maps to be assessed at a general scale and major areas of disagreement to be identified for closer evaluation. For example, in Figure 2, a similar broad-scale drought signal was detected for western Nebraska in both VegDRI and USDM maps, as well as the early-stage drying conditions over eastern Nebraska.

3) *Expert feedback*: A network of expert evaluators that includes state climatologists, USDM authors, rangeland/crop experts, and agricultural producers from across the United States are evaluating the accuracy of the VegDRI maps throughout the growing season for their local area and providing both qualitative and quantitative feedback. Expert evaluation of the VegDRI maps began in 2007 and the results are currently being summarized.

Further quantitative comparisons of VegDRI to biophysical vegetation measurements (e.g., biomass and leaf area index) from various clip plot datasets, soil moisture measurements from state Mesonets and other networks, and USDA crop yield data are planned.

4. Future Work

Several research initiatives are under way or planned to enhance the current VegDRI model, including:

- A transition to time-series 1-km NDVI data from MODIS is planned to capitalize on the high-quality data stream provided by this new global imager. Research is being conducted to crosswalk AVHRR and MODIS NDVI data and develop a comparable intersensor NDVI time series. Once an intersensor NDVI time series is completed, VegDRI will use the historical time series of NDVI observations from AVHRR for model development and apply the models to crosswalked MODIS NDVI data for near-real time production of VegDRI maps. The models will also be applied to the 250-m MODIS NDVI data in an effort to develop a higher resolution VegDRI product.
- The incorporation of a temperature component into the VegDRI model will also be explored through the use of thermal imagery. New indices derived from satellite-based thermal observations, such as the evaporative stress index (ESI) (Anderson et al., 2007), will be tested.
- Higher resolution soil information from the Soil Survey Geographic (SSURGO) Database will also be evaluated in an effort to better parameterize the spatial variability and characteristics of soils in the VegDRI model.
- Alternative temporal modeling windows (e.g., multiple period, moving windows) are being tested to further enhance the current VegDRI models and make the approach more flexible as VegDRI production expands to other areas of the United States.

5. Summary

VegDRI is a new, national-level drought monitoring tool that provides near-real time, 1-km resolution maps that depict the geographic extent and severity of drought conditions on vegetation. The integration of 1-km vegetation condition observations, derived from AVHRR NDVI data, with climate-based drought index data and other biophysical information in the VegDRI model enables higher resolution drought monitoring information to be generated. The improved, 1-km resolution of VegDRI provides drought information at a more relevant spatial scale for local-scale planning, mitigation, and response activities than the common drought indicators that are currently being used. As a result, the VegDRI could be used by a broad user community that includes agricultural producers, drought and natural resource specialists, policy makers, and other stakeholders to make more informed decisions at national, regional, state, and county levels.

6. References

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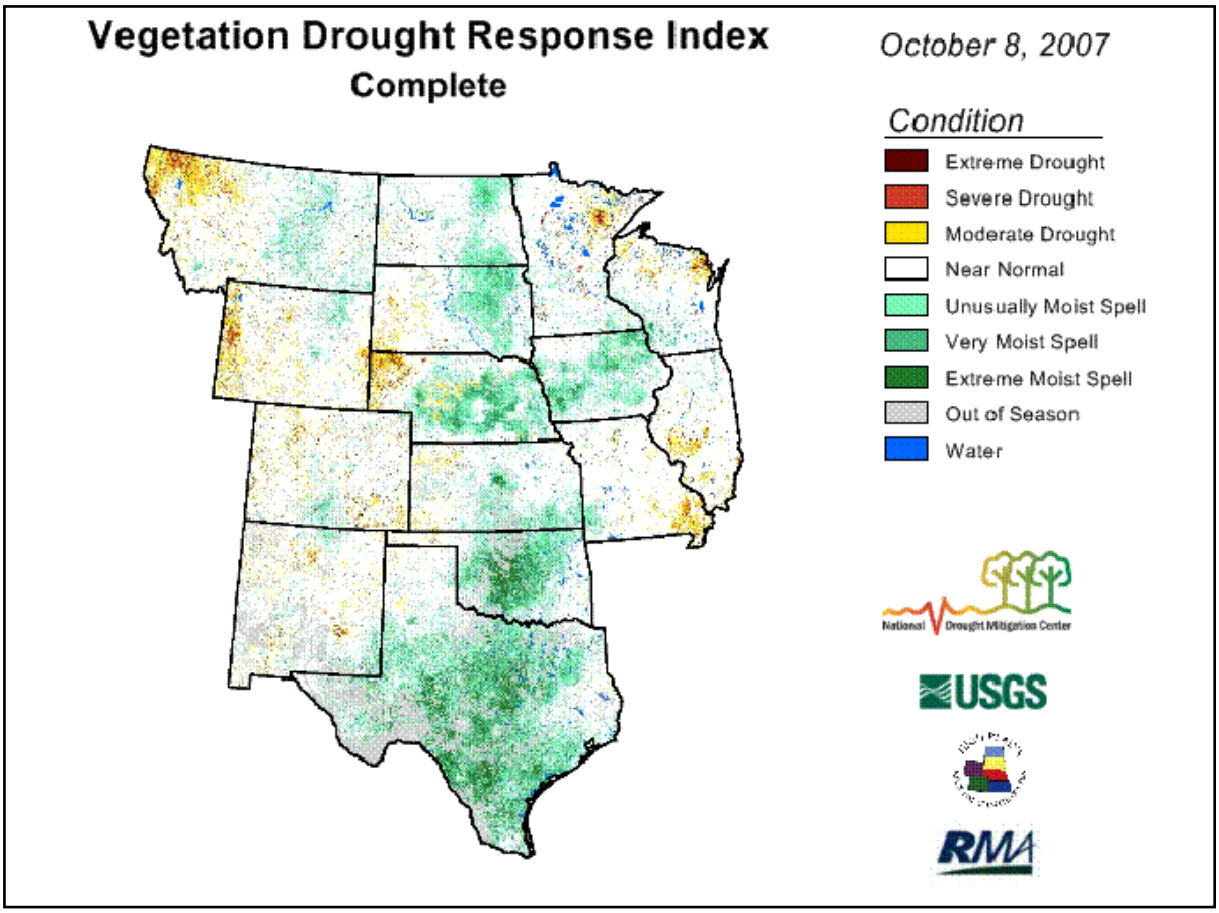

Figure 1. Operational VegDRI product for October 8, 2007, for a 15-state region of the central United States.

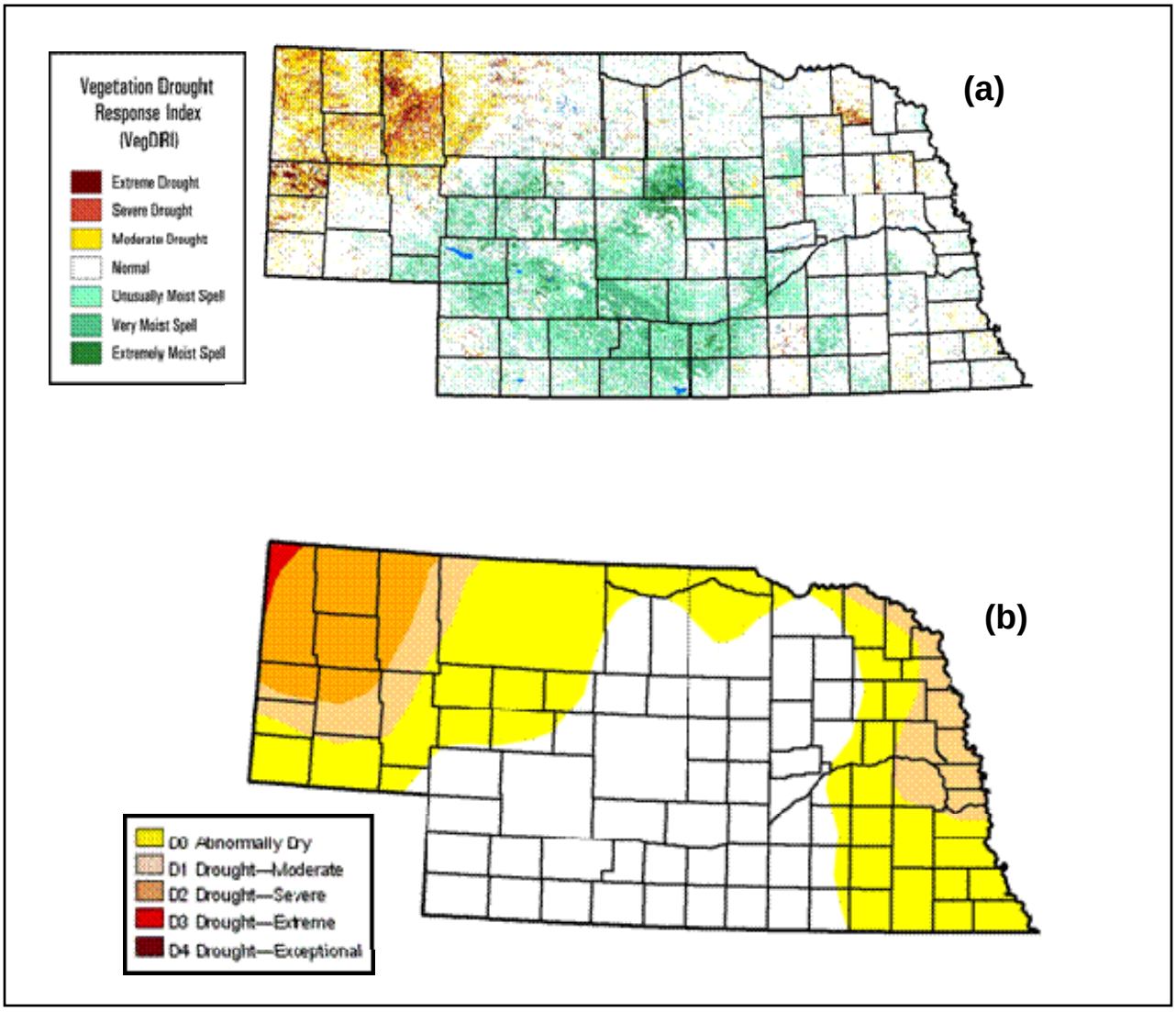

Figure 2. (a) VegDRI for July 30, 2007 and (b) the U.S. Drought Monitor for July 31, 2007. (Note: White areas indicate no drought in Figure 2b.)

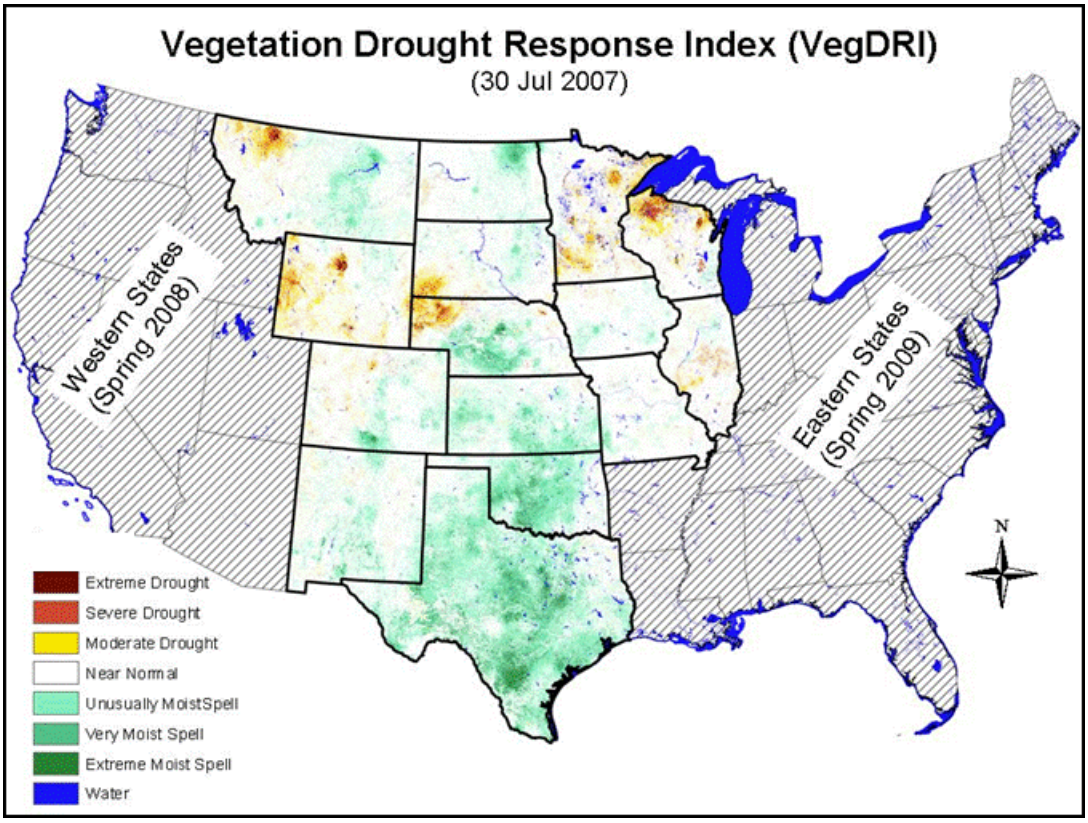

Figure 3. Map of geographic expansion schedule for operational VegDRI production.

Table 1. Data inputs for the VegDRI model

Data Set Name	Type	Acronym	Source	Temporal Frequency	Format	Reference(s)
Standardized Precipitation Index	Climate	SPI	ACIS/NADSS	biweekly	Ascii (at sites) and 1 km raster surface	Edwards and McKee, 1997
Palmer Drought Severity Index (Self-calibrated)	Climate	PDSI	ACIS/NADSS	biweekly	Ascii (at sites)	Palmer, 1965 Wells et al., 2004
Percent of Average Seasonal Greenness	Satellite	PASG	AVHRR NDVI	biweekly	1 km raster	Brown et al., in press
Start of Season Anomaly	Satellite	SOSA	AVHRR NDVI	annual	1 km raster	Brown et al., in press
Land Cover	Biophysical	LC	National Land Cover Database	static	1 km raster	Homer et al., 2004
Soil Available Water Capacity	Biophysical	AWC	STATSGO	static	1 km raster	USDA, 1994
Irrigated Agriculture	Biophysical	IrrAg	USGS EROS / NDMC	static	1 km raster	
Ecological Regions	Biophysical	ECO	EPA Ecoregions	static	1 km raster	Omernik, 1987
Elevation	Biophysical	ELEV	GTOPO30	static	1 km raster	Gesch et al., 1999

Table 2. Seasonal VegDRI modeling phases

Phase	Start Date	End Date	General Growth Stage
Spring	mid-April	mid-June	Emergence, early growth
Summer	mid-June	end of August	Maturity, peak growth
Fall	end of August	early October	Senescence, harvest

Table 3. VegDRI product characteristics.

Monitoring target	Vegetation stress (drought-caused)
Source instrument, mission, processing chain	AVHRR instrument NOAA-11, -14, -16, -17 missions VegDRI processing chain
Product description	Gridded index modeled after the Palmer Drought Severity Index
Spatial resolutions	1,000-m
Geographic map projection	Lambert Azimuthal Equal Area
File format	Geotiff (planned in 2009)
Geographic extent	7 states in 2006 15 states in 2007 22 states in 2008 48 states in 2009
Product frequency	14-day (in near real time during 2006-2008) 7-day (2009 forward planned)
Product delay (or Latency)	~ 24 hours from last observation
Period of record	1989-current (historical reprocessing for 22 states planned in 2008)
Gaps (or time-series heterogeneity)	None
Product access (anonymous FTP)	http://gisdata.usgs.net/website/Drought_Monitoring/viewer.php http://www.drought.unl.edu/vegdri/VegDRI_Main.htm ftp product distribution planned in 2009
Compatibility with commonly used software	Yes
Relevant citations	Brown et al., in press.