Monitoring Drought Stress across Multiple Vegetation Types within the Upper Colorado River Basin

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1. Introduction

Drought events have been frequent, prolonged, and often severe in the Upper Colorado River Basin (UCRB) and indeed, over much of the intermountain West, during the late 20th and early 21st centuries (Andreadis and Lettenmaier 2006). Conditions have been especially dry from 2000 forward. In certain instances, drought events spanned multiple years, increasing impacts on society and the environment. Recent impacts that have been associated with drought have included wildfires, major forest die-back, reduced agricultural productivity, and less water availability for municipal and agricultural use.

2. Background and Rationale

Scientists at the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center and the National Drought Mitigation Center (NDMC) have developed a drought monitoring methodology to address the considerable spatial and temporal variability of drought called the Vegetation Drought Response Index (VegDRI; (Brown et al. 2008). The VegDRI tool was originally designed to convey the spatial, temporal, and intensity of drought conditions with improved response time depicted by the U.S. Drought Monitor (USDM).

VegDRI is based on models that integrate satellite-based Normalized Differenced Vegetation Index (NDVI) data along with biophysical variables and historical and near-real time climate data to create a tool to monitor drought stress in vegetation. This tool provides more spatially-precise information than many traditional drought indices (e.g. Standardized Precipitation Index). The integration of the NDVI and other observations into the VegDRI methodology provides near-real time creation of spatially continuous, relatively detailed (1 km^2), biweekly and weekly map products showing drought conditions across the conterminous United States (Figure 1). Near-real time access to data and maps is provided from two main map services (*http://www.drought.unl.edu/vegdri/VegDRI_Main.htm* and *http://vegdri.cr.usgs.gov/viewer/viewer.htm*). Operational VegDRI information is provided at spatial and temporal scales relevant to decision makers working at local to national levels.

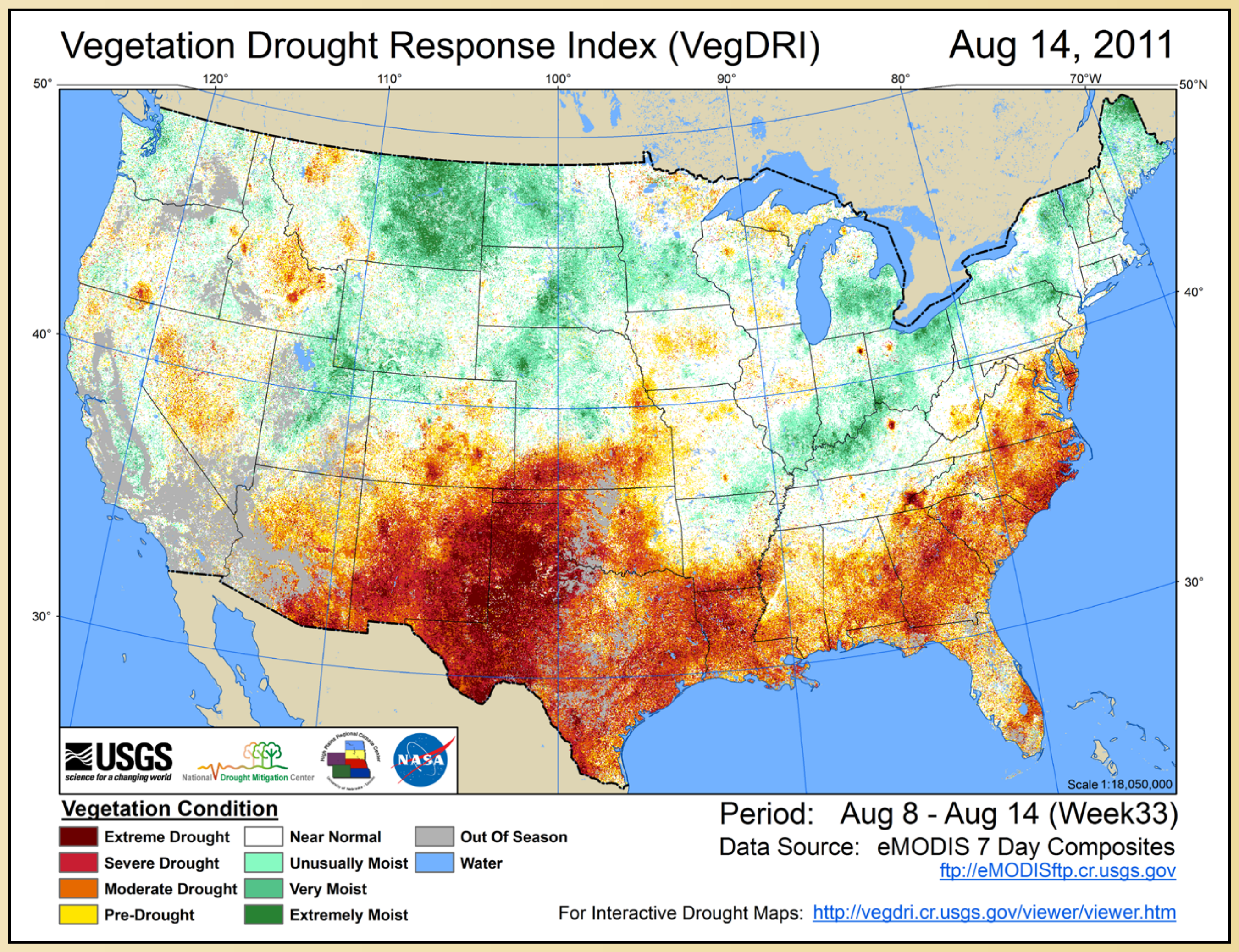

Figure 1. The Vegetation Drought Response Index for August 14, 2011.

We used an historical record of the VegDRI from 1989 to 2010 for a geographically-detailed analysis of multi-year drought effects on vegetation across the UCRB. We analyzed drought patterns in spatial and temporal domains within various vegetation types (e.g. forests, shrublands, and grasslands) and investigated the spatial and temporal variability in seasonal and cumulative drought stress.

3. Methods and Data

This study characterizes the record of drought events and explores their geographic extents, durations, and severity across the UCRB (Figure 2) during the 21-year study period (1989 to 2009). The digital data sets that contributed to this analysis included:

1. An historical record of VegDRI (Brown et al. 2008)
2. Six-digit hydrological units (HUCs; (Seaber et al. 1994)
3. 2001 National Land Cover Database (NLCD; (Homer et al. 2007)

Figure 2. The Upper Colorado River Basin study area.

VegDRI models incorporate three basic types of input data: satellite imagery, climate data, and biophysical variables (Figure 3). Each input type contributes important information about vegetation drought stress. A satellite-based measure of relative vegetation condition, the NDVI acquired by the Advanced Very High Resolution Radiometer (AVHRR) sensor carried aboard National Oceanic and Atmospheric Association (NOAA) weather satellites is integral to VegDRI. Analyzed over time, it is used to calculate certain variables or metrics that are incorporated into VegDRI models as a way to quantify seasonal and anomalous variability in vegetation conditions. Combining the NDVI with climate data in a modeling scenario reveals where vegetation is stressed due to drought as opposed to other environmental factors (e,g,, hail, flooding, overgrazing). Vegetation drought stress can vary greatly depending on land cover type, soil characteristics, land use practices, and elevation. In order to represent such environmental differences, VegDRI models also include information about soils, land cover, irrigation, and elevation derived from a variety of data sources.

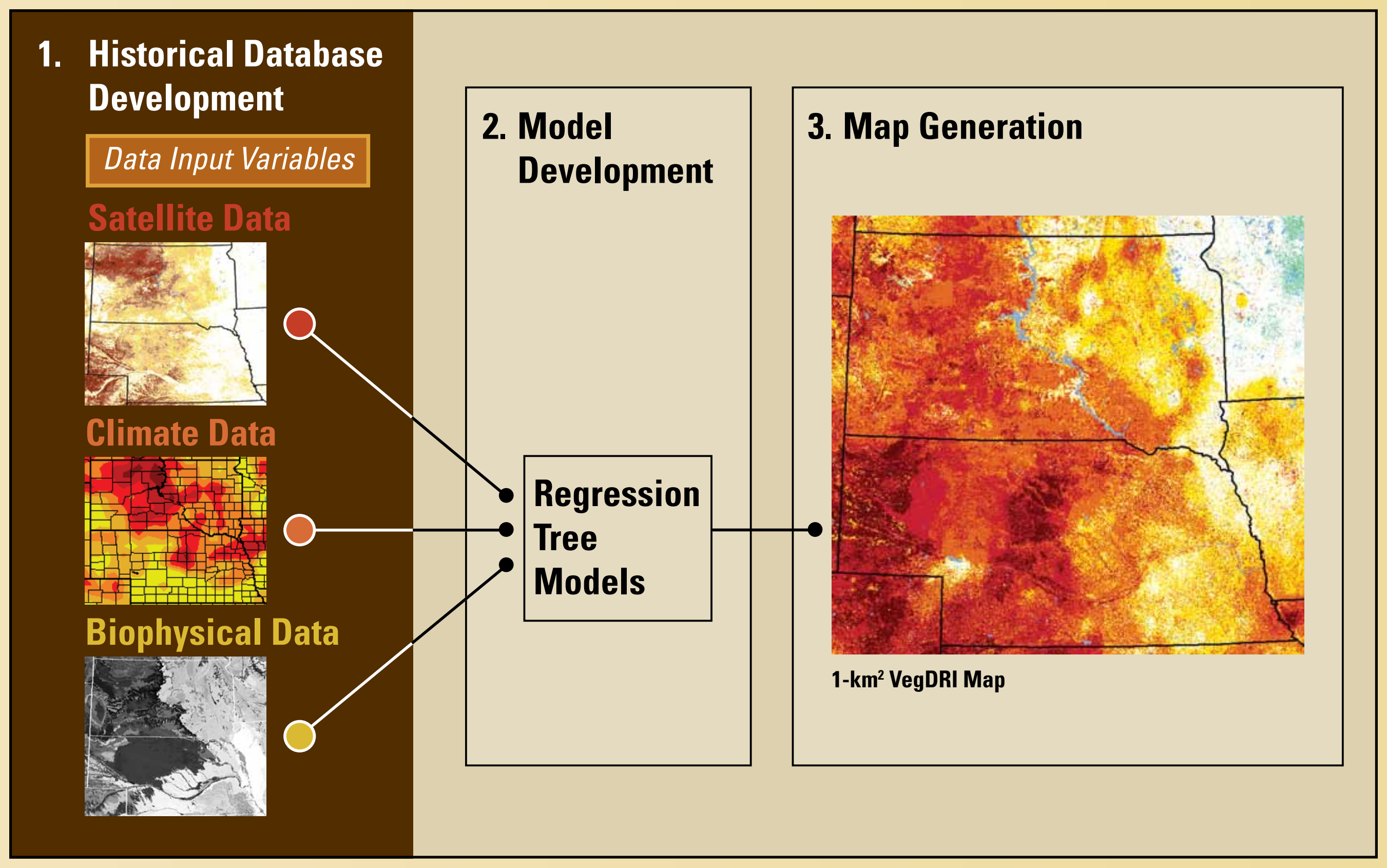

Figure 3. The VegDRI modeling methodology.

VegDRI has eight vegetation condition classes (Table 1) based on a modified version of the PDSI classification system (Palmer 1965). There are three classes of drought severity (moderate, severe, and extreme), as well as a pre-drought class that represents the dry side of near-normal class value range. The pre-drought class was included to highlight areas that may be nearing initial drought conditions. VegDRI also has four non-drought classes (normal, and unusually, very, and extremely moist) that characterize locations with normal to better than normal vegetation conditions, as well as areas of excessively wet conditions that could result in poor vegetation conditions due to flooding. An 'out of season' (OS) class is also included to identify time periods for a given location when the vegetation is dormant (e.g., winter months) and VegDRI values are not calculated.

Table 1. VegDRI ranges and category names.

VegDRI Class Names	Value Range
Extreme Drought	< -4
Severe Drought	-3 to -4
Moderate Drought	-2 to -3
Pre-Drought	-1 to -2
Near Normal	+2 to -1
Unusually Moist	+2 to +3
Very Moist	+3 to +4
Extremely Moist	> +4

In this study, only the growing season months of May through September were taken into account for the drought analysis as VegDRI is an indicator of vegetation stress due to drought and is only pertinent during the growing season. Individual pixels designated as OS during May through September were also withheld from further analysis. The weekly VegDRI data were summarized into monthly time steps by calculating the average of all data within each month.

Land Cover and Hydrologic Units

The spatial units for analyzing and characterizing drought within the UCRB were an important feature of this study. Our purpose was to segment the study area into meaningful and recognizable geographic areas that were associated with comparable regions on the ground.

The desired analysis was generalized over an individual pixel level, which would have been difficult to simplify (approximately 293,000 individual 1 km^2 pixels are in the UCRB) but facilitated meaningful comparisons within different parts of the UCRB. One of the strengths of VegDRI is its 1 km^2 geographic detail and this method of analysis seeks to capitalize on the increased spatial variability in drought impacts at this relatively high resolution.

We utilized hydrologic units and land cover types to designate the spatial analysis units for the study. Specifically, we integrated the accounting units (or 6-digit units) of the hydrologic unit maps of the United States (Sheffield et al. 2009) and a generalized and resampled version of the National Land Cover Database (NLCD). Our analysis incorporated these ten 6-digit HUCS in the UCRB (i.e., 121, 145, 157, 167, 182, 191, 193, 198, 215, 219; see figure 4) and five generalized land cover types (cropland, forest, herbaceous, shrubland, and wetlands). Very few wetlands were found in the UCRB and those results were not summarized here. Through the integration of these two geographic data sources, 139 unique spatial zones (HUC-LC zones) were established in the UCRB. VegDRI was masked for OS and the spatial mean and median monthly VegDRI was calculated for each month within each HUC-LC zone.

Drought Extent, Severity, and Duration

Drought events in the UCRB were identified using a methodology based on drought extent, duration, and severity (EDS). This approach has roots in the severity-area-duration (SAD) methodology demonstrated by (Sheffield et al. 2009). In that study, the authors identified global droughts using a clustering algorithm run on simulated soil moisture data over a 50-year period (1950-2000). Instead of a clustering algorithm to identify events, we employed the HUC-LC geospatial units to calculate indicators for drought extent, drought severity, and drought duration. Through employing sub-basin geospatial analysis units, we undertook characterizing and comparing drought events in the UCRB. The four major generalized land cover types were also used to explore and characterize the impact of drought events on different cover types.

We used the following formula for calculating the EDS:

EDS = Extent X Duration X Severity

where Extent = # HUCs in which VegDRI < -2.0 (upper range for moderate drought).
Duration = # consecutive months in the growing season in which VegDRI < -2.0 summed for all HUCS and divided by # HUCS (10).
Severity = |Mean VegDRI| severity for each HUC for each year.

The EDS is a unitless index and is comparable across the UCRB in this study. To expand this analysis to other basins, the EDS would need to be standardized for the number of HUCs present in each basin.

4. Results

Drought Extent, Severity and Duration

The VegDRI and EDS analysis revealed that the top five drought events, in order of magnitude, were 2002, 1989, 1994, 2000, and 1996 (see Table 2). The 2002 drought (EDS=144) was by far the worst event in this 21-year period. The 2002 drought was an extreme event for multiple reasons. First, the extent covered the entire basin; all 10 HUCs showed the presence of moderate to severe drought. Second, the duration of the drought was all growing season long (5 month span). Third, the average severity in VegDRI was -2.88.

Based on this technique using VegDRI and the EDS, the recent decade (with the clear exception of 2002) appeared have fewer severe events compared with the late 80s/early 90s. However, nearly all the years from 2000 to 2009 showed some level of drought or dryness in the UCRB indicating a multi-year event, even though many of the drought effects were less severe than 2002.

Table 2. Upper Colorado River Basin droughts sorted by extent, duration, and severity results.

Year	Extent	Duration	Severity	EDS
2002	10	5	2.88	144.25
1989	9	1.8	1.43	23.10
1994	6	1.9	1.38	15.68
2000	6	1.4	1.30	10.95
1996	5	1.6	1.04	8.29
1990	4	0.7	1.16	3.26
2006	3	0.8	1.14	2.73
2001	2	0.8	0.65	1.04
2003	3	0.3	0.79	0.71
2007	2	0.5	0.67	0.67
2005	1	0.4	0.90	0.36
2008	2	0.4	0.36	0.29
2009	3	0.3	0.15	0.14
1992	2	0.2	0.09	0.04
1991	0	0	0.40	0.00
1993	0	0	1.04	0.00
1995	0	0	1.66	0.00
1997	0	0	1.15	0.00
1998	0	0	0.09	0.00
1999	0	0	0.62	0.00
2004	0	0	0.76	0.00

Drought Effects in Different Land Cover Types

The discussion focuses on the drought effects related to the five most extreme droughts (see Table 2) in regions of the UCRB by land cover type. We describe these drought events within Wyoming, Utah, Colorado, and New Mexico. In the northern part of the UCRB (Wyoming: HUCs 121, 145), the 1989 drought showed only very mild drought effects. The 1994 drought showed moderate drought effects mainly in croplands, but not as severe in other HUC-LC types. The drought in 1996 had less effect on Wyoming HUCs than other droughts in this 21-year period. The major 2002 drought appears to have begun in 2001 in the north, and the effects were moderate and severe in HUC145. After 2002, there were some mild to moderate drought effects during 2006, 2007, and 2008 that were worst in HUC145.

The western section of the UCRB (Utah; HUCs 167, 193, 215) depicted just slightly moderate drought effects in shrub, herbaceous, and croplands in 1989 and actually, lower VegDRI (in the moderate drought category) followed in 1990. In 1994 and again in 1996, lands in southern Utah (HUC 193) showed the greatest drought effects. The drought in 2000 did not greatly impact the western edge of the UCRB, however, this part of the basin was hardest hit by the drought in 2002, with moderate-severe-extreme drought across all land cover types with particularly severe conditions in August. Since 2002, most years have been below normal in this area, with the exception of 2005, which showed VegDRI in the "unusually moist" range, indicating substantial opportunity for vegetation recovery.

Colorado and New Mexico HUCs (157, 191, 182, 198, 219) were merged for the sake of this discussion. The 1989 drought event appeared to affect the center of the UCRB quite severely—in fact, the eastern edge of the UCRB shows lesser drought effects in 1989 recovering to above normal by early 1990. In 1994, northwestern Colorado (HUCs 157, 182) depicted poorer vegetation conditions in all cover types than further south. The drought event in 1996 showed more severe effects on the southern part of the UCRB. In fact 1996 was the second "worst" drought event in HUCs 191 and 219. In Colorado and New Mexico, 2000 registered as more of a mild drought event. In 2002, all HUC-LC zones showed moderate to severe impacts, but HUC 198 seemed more severely impacted. The years since have been mainly near normal. However, 2006 and 2007 showed some fairly significant drought impacts especially in the south.

5. Conclusions

This study provides drought information depicting the level of vegetation stress in major land cover types across the UCRB. The most severe drought effects (supported by the EDS analysis) occurred across the entire UCRB during the growing season in 2002 and were apparently more severe along the eastern flanks of the basin. Although extreme, the 2002 drought is also significant in that it is part of a multi-year event where prolonged dry conditions have not allowed for much recovery. Another drought in 1989 showed broad impacts, occurring in 9 out of 10 HUCs in the basin but was generally less severe.

This type of analysis utilizing a geospatial drought indicator such as the VegDRI allows a new and different view of drought impacts as these influence the health, production, and condition of each major land cover class. Many applications might take advantage of this additional information (e.g., rangeland and forest management, ecological studies, etc.) Land owners, managers, and policy makers can use this information to assist their plans for management of forests, rangeland, and other natural areas under current and future conditions. Further analysis is planned to evaluate this index in the context of regional drought impacts within the UCRB and other major river basins in the U.S.

6. References

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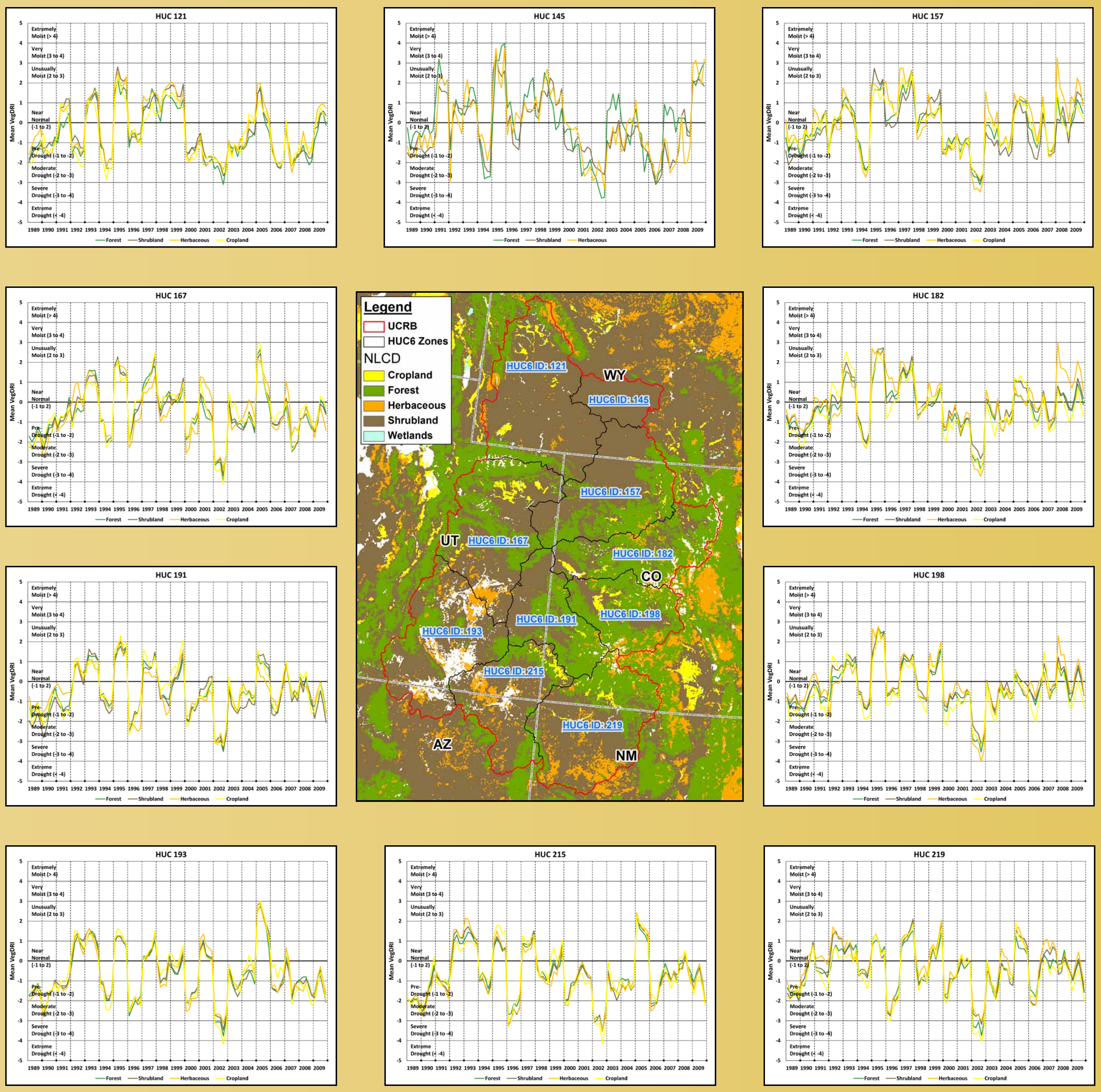

Figure 4. Time-series VegDRI plots for the HUC-LC types in the Upper Colorado River Basin.

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