AGRICULTURAL DROUGHT MONITORING FROM SPACE USING FREELY AVAILABLE MODIS DATA AND IMPACTS ON COTTON COMMODITY

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ABSTRACT

During the last decade, the State of Texas, USA has suffered from several severe to extreme agricultural droughts, which caused significant decreases in cotton yields, especially in 2006, 2008, 2009 and 2011. Texas alone has been accounted for approximately 50% of the acres of upland cotton planted in the U.S. In the event of an agricultural drought solely in Texas, the total cotton production in the U.S. would be greatly reduced. This paper discusses the detection of agricultural droughts over cotton fields in Texas between 2000 and 2011 by using freely available remote sensing data and the implications of these drought events on cotton yield and cotton price. Remotely sensed vegetation condition indices, such as the normalized difference vegetation index (NDVI) and the vegetation condition index (VCI), are prominent indictors of vegetation health conditions. The temperature condition index (TCI) is a supplement to the vegetation indices and provides general information about thermal conditions in an area of interest. Because agricultural drought will cause stress on vegetation, remotely sensed vegetation condition indices along with the temperature index can be used to monitor agricultural droughts. Multiple agricultural drought maps have been generated by using those indices for the years from 2000 to 2011. We found that the northern, western and northwestern Texas were exposed to severe to exceptional droughts during the most active planting season of the upland cotton. In comparison to our findings, the U.S. Drought Monitor (USDM) operated by NOAA reported extreme to exceptional droughts in the northern, western and northwestern parts of Texas for the same periods. However, our agricultural drought maps and USDM maps did not agree in term of the spatial distribution of agricultural droughts in other parts of Texas. In addition, when night temperature products derived from the MODIS instrument onboard Aqua satellite were added into the agricultural drought monitoring algorithm, they unrealistically reduced the intensity of agricultural droughts. This study suggests that freely available satellite data can be used to monitor agricultural drought events with satisfactory result, and such information can be further used to predict the crop yields and prices.

Keywords: Agricultural Drought, Agricultural Drought Monitoring, MODIS, Cotton, Crop yield, Texas

INTRODUCTION

One of the significant impacts of agricultural droughts is the dramatic fall in yield of almost every kind of crop, such as cotton, corn, and soybeans. Weather-related abiotic factors play a major role in the amount of foods available to humanity each year all over the world, causing regular and sometimes sharp fluctuation of crop yields and prices. Extreme temperatures in a warming global climate are partly attributed to the increase of severity of agricultural droughts.

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The State of Texas, USA has been suffering from several severe to extreme agricultural droughts since the beginning of the millennium. The damage in cotton yields collectively caused a hike in cotton price (U.S. Department of Agriculture - National Agricultural Statistics Service (USDA-NASS) 2011). Figure 1 shows the time series of the cotton price in Texas between 2000 and 2010. Texas suffered from the extreme to exceptional agricultural droughts at the highest intensity in the 2011 (Tinker 2011; Miskus, Rosencrans, and Artusa 2011; Miskus 2011a; Miskus 2011b; Artusa 2011) growing season of the cotton crop and relatively mild-severity agricultural droughts in 2008 (James 2008a; James 2008b; Miskus 2008a; Miskus 2008b) and 2009 (Edwards, Miskus, and Rosencrans 2009; Artusa, Miskus, and Rosencrans 2009a; Artusa, Miskus, and Rosencrans 2009b; Artusa, Miskus, and Rosencrans 2009c). As a result of three consecutive agricultural droughts in the last 4 years, the cotton price hits all-time high.

As shown in Figure 2, Texas alone has been accounted for approximately 50% of upland cotton acreage in the United States since 2000 (U.S. Department of Agriculture - National Agricultural Statistics Service (USDA-NASS) 2011). The cotton statistics are based on the annual surveys made by the U.S. Department of Agriculture, National Agriculture Statistics Service (USDA-NASS) between 2000 and 2011.

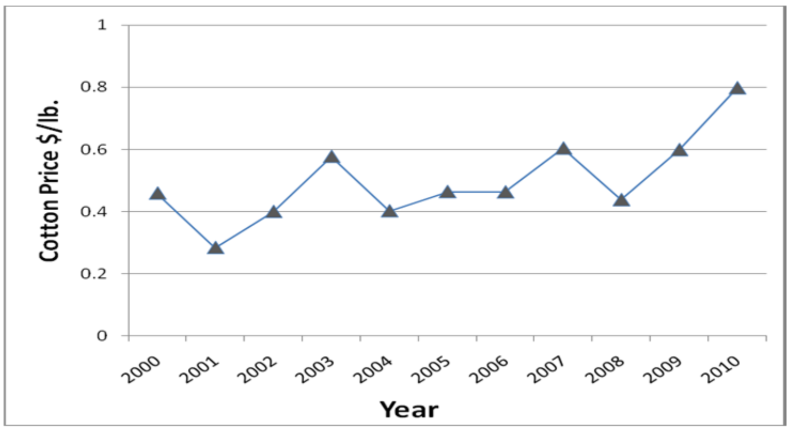

Figure 1. Cotton Prices in Texas between 2000 and 2010 in dollars per pound units ($/lb).

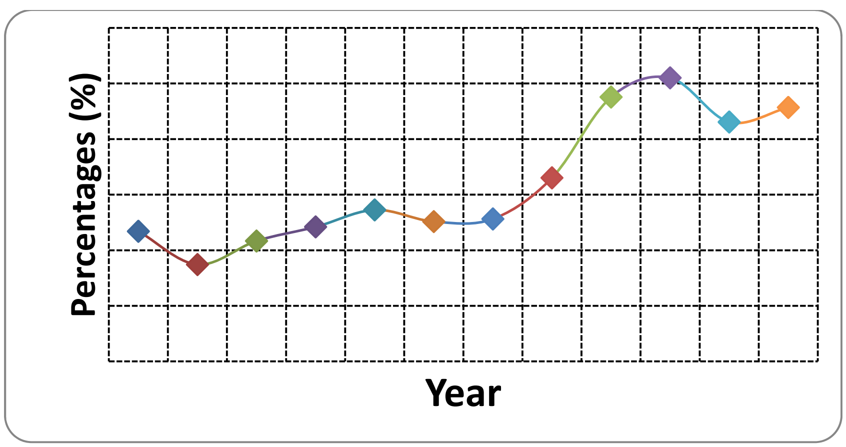

Figure 2. The ratio of the acres of upland cotton planted from 2000 to 2011 in the state of Texas to that in the US in percentage (%).

Various drought algorithms and indices, which fuse drought-related parameters such as vegetation greenness, temperature, evapotranspiration, rainfall, soil moisture, and vegetation moistures, have been developed and widely used by scientists for agricultural drought monitoring and analysis (Wang and Qu 2007; Brown et al. 2008; Gao 1996; Anderson et al. 2010; Xu et al. 2011; Quiring and Papakryiakou 2003; Heim 2002; Kogan 2002). Agricultural drought indices derived from satellite remote sensing have drawn many scientists' attention lately because of high spatial resolution, large spatial and frequent temporal coverages, and their ability to detect droughts timely and objectively (Kogan 1995).

At present, the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) are the most popular sensors, widely used in drought monitoring applications (Rojas, Vrieling, and Rembold 2011). The MODIS and AVHRR sensors are suitable for monitoring land surface dynamics and environment. As one example, the vegetation greenness derived from the MODIS data, as an indicator of adverse weather conditions on the grape harvest, was able to satisfactorily track down agricultural droughts in Aegean of Turkey (Yagci et al. 2011).

Remotely sensed vegetation condition indices, such as the normalized difference vegetation index (NDVI) and the vegetation condition index (VCI), satellite-derived temperature indices such as the temperature condition index (TCI), and combination of vegetation greenness and temperature indices such as vegetation health index (VHI) have been developed and widely applied to identify agricultural droughts through monitoring vegetation health and temperature conditions of vegetation canopy using AVHRR data at regional to global scales (Brown et al. 2008). Besides AVHRR data, those indices can be calculated using MODIS data, which provides higher spatial resolution (250 meters) than the coarse resolution AVHRR data (1 km to 4 km).

This paper discusses the detection of agricultural droughts over cotton fields in Texas between 2000 and 2011 by using freely available remote sensing data and the implications of these drought events on cotton yields and prices.

DATA AND METHODS

The MODIS surface reflectance products at 250m spatial resolution and 8-day temporal resolution (MOD09Q1.005) from the Terra satellite and the MODIS land surface temperature (LST) & Emissivity product at 1km spatial resolution and 8-day temporal resolution (MYD11A2.005) from the Aqua satellite were retrieved in the Hierarchical Data Format (HDF-EOS) from the NASA's Land Processes Distributed Active Archive Center (NASA LP DAAC) ftp website, which can be accessed at ftp://e4ftl01.cr.usgs.gov/MOLT/MOD09Q1.005. Each MOD09Q1.005 data granule is comprised of two spectral bands, measured in the Red and Near-Infrared (NIR) region of the electromagnetic spectrum respectively, while each MYD11A2.005 data granule consists of both daytime and nighttime land surface temperature. Additionally, the land water masks (MOD44W.005) were downloaded from the above ftp website to mask water bodies out of the final outputs of agricultural drought indices. The 2010 administrative areas of Texas at both state and county levels have been obtained from the website of the geography division of the U.S. Census Bureau in Esri's shapefile format, which may be accessed at http://www.census.gov/geo/www/tiger/tgrshp2010/tgrshp2010.html.

It was reported that the most active planting dates of the commodity cotton crop are between April 8 and June 7 (U.S. Department of Agriculture - National Agricultural Statistics Service (USDA-NASS) 2010). In the first step of this study, NDVI time series during the most active planting dates of the cotton between 2000 and 2011 were calculated from MOD09Q1.005, and then each VCI at 250m spatial resolution and 8-day temporal resolutions was constructed using previously calculated NDVI time series of 12 years long. Each TCI was calculated from the MYD11A2.005, the MODIS daytime and nighttime land surface temperature products. In the next step, multiple VHIs were computed with the following combinations: (1) 0.5 * VCI + 0.5 * TCI from daytime temperature, (2) 0.5 * VCI + 0.5 * TCI from nighttime temperature, and (3) 0.5 * VCI + 0.5 * TCI from average of daytime and nighttime temperature. All above-mentioned index images derived from MODIS products were clipped by the Texas state shape file in the final step. All the equations used to compute the indices above are given in Table 1.

Four different types of agricultural drought maps have been selected for consideration; a VCI drought map, a VHI map calculated from daytime temperature of TCI, a VHI map calculated from nighttime temperature of TCI, a VHI map calculated from average temperature of TCI. The agricultural drought severity classification scheme utilized in our study is adopted from the U.S Drought Monitor's (USDM) classification scheme, which includes abnormally dry, moderate drought, severe drought, extreme drought, and exceptional drought in ascending order of severity. It has been suggested by (Kogan 2002), that VHI < 40 indicates drought related vegetation stress, that is to say, agricultural drought. In this study, we used the classification schema shown in Table 2 to map the VHI and VCI values to the level of agricultural drought severity.

Table 1. The equations of agricultural drought indices

Index Name	Formula
NDVI	(NIR – RED) / (NIR – RED)
VCI	(NDVI – NDVImin) / (NDVImax – NDVImin)
TCI	(LSTmax – LST) / (LSTmax – LSTmin)
VHI	a * VCI + (1 – a) * TCI

Table 2. Agricultural Drought Classification Scheme

Category	VHI or VCI
abnormally dry	$40 \geq x > 32$
moderate drought	$32 \geq x > 24$
severe drought	$24 \geq x > 16$
extreme drought	$16 \geq x > 8$
exceptional drought	$8 \geq x \geq 0$

ANALYSIS OF RESULTS

For comparison purposes, drought maps compiled by USDM are shown in Figure 3, whereas the four different types of agricultural drought maps constructed from different combination of VCI and TCI are shown in Figure 6. U.S. Drought maps in Figure 3 clearly indicate that Texas was overwhelmed by both agricultural and hydrological droughts at extreme to exceptional levels during the most active planting season of cotton crop in 2011. Note that, A and H in U.S Drought Monitor's maps denote agricultural drought and hydrological drought, respectively. In the same way, our maps in Figure 6 captured agricultural drought at varying severity levels mostly in the northern, western and northeastern parts of Texas. In particular, the VCI maps show extreme to exceptional vegetation stress conditions in the northern, western and northeastern Texas, which match with the extreme to exceptional droughts in the areas reported by USDM in Figure 3. However, the VCI maps show no substantial vegetation stresses over eastern and southeastern Texas in 2011 during the most active cotton planting season that does not match the USDM drought report shown in Figure 3. If we take a look at the VHI drought maps constructed with LST night temperature - the second line in Figure 6 - as well as the VHI constructed with LST average of day and night temperature - the fourth line in Figure 6 -, the extreme to exceptional drought areas observed by VCI are reported to be either abnormally dry to moderate agricultural drought or no drought at all. The VHI calculated by 0.5 * VCI + 0.5 * TCI (LST day) shows that the panhandle and southwestern of Texas were at the same extreme to exceptional drought conditions as in VCI vegetation stress maps, which matches the USDM drought maps, whereas the western Texas wasn't much suffered from extreme to exceptional drought as reported by the USDM. To be more specific, the western Texas was under the abnormal dry to moderate drought conditions in 2011. Similarly, VCI drought maps were not able to capture considerable area of moderate to exceptional agricultural droughts in the same area. The extreme to exceptional agricultural droughts during the last two week of the most active cotton planting season were captured by all our four agricultural drought maps. Overall, VCI vegetation stress maps and the VHI constructed with TCI (LST daytime temperature) showed relatively identical spatial patterns of drought at broad-scale.

To assess the accuracy of drought monitoring maps, the upland cotton yield should be collected for San Patricio and Nueces counties, located in the southeastern part of Texas, where mild to exceptional drought conditions weren't observed in the drought maps, and for Terry, Lyrin, Dawson, Hockley, and Hale counties, situated in the north and northwestern regions of Texas, where substantial extreme to exceptional agricultural drought was reported during the most active planting season for upland cotton. These counties have the largest share of the cotton planting areas in Texas. At the time of writing this paper, the upland cotton yields aren't available at the USDA-NASS

Website. Without the upland cotton yields, it is very difficult to say which of the agricultural drought maps is more accurate.

The statistics obtained from USDA-NASS Website in Figure 4 show that there are relatively large differences between the planted and harvested upland cotton acreages in years 2006, 2008, 2009 and 2011, with the largest in 2011 when the extreme to exceptional agricultural drought occurred concurrently. In 2011, almost half of the planted upland cotton crop was lost mainly due to the agricultural drought. Furthermore, the crop yields are calculated as total upland cotton production in pounds divided by the planted acreage, and divided by the harvested acreages (Figure 5). From Figure 5 we can conclude that although the 2011 extreme agricultural drought has destroyed many acres of cotton crops, the yield of the survived cotton crops doesn't drop much.

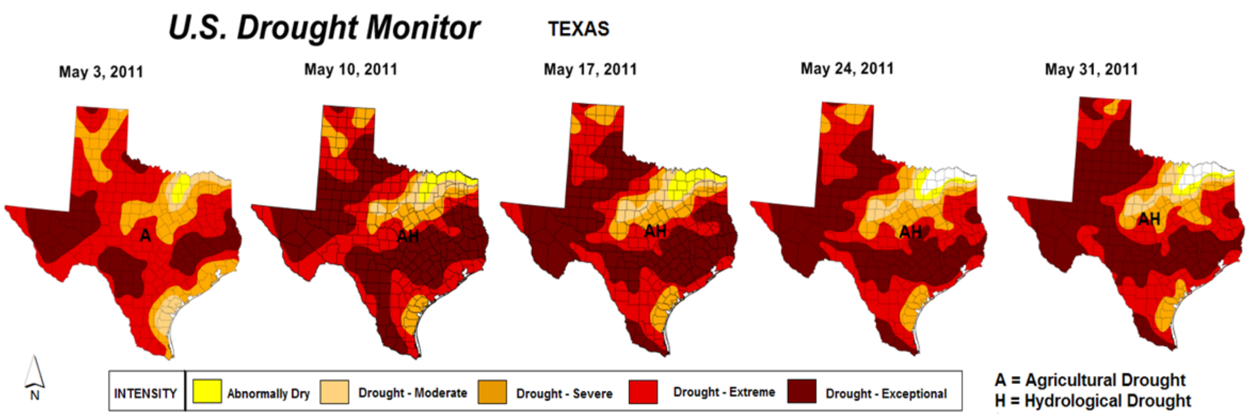

Figure 3. U.S. Drought Monitor maps between May 3 and June 6, 2011 (Tinker 2011; Miskus, Rosencrans, and Artusa 2011; Miskus 2011a; Miskus 2011b; Artusa 2011).

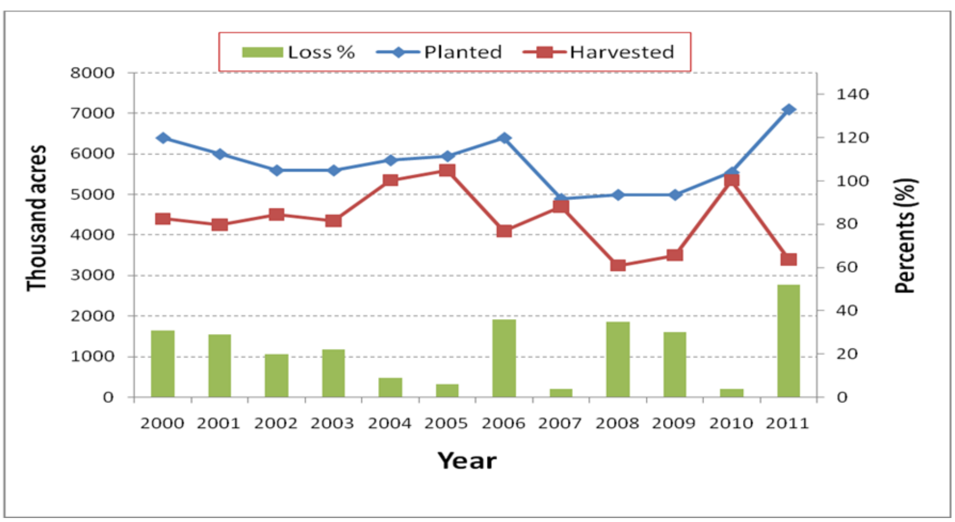

Figure 4. The statistics of planted and harvest upland cotton acreages in Texas between 2000 and 2010, and difference between two in percentages.

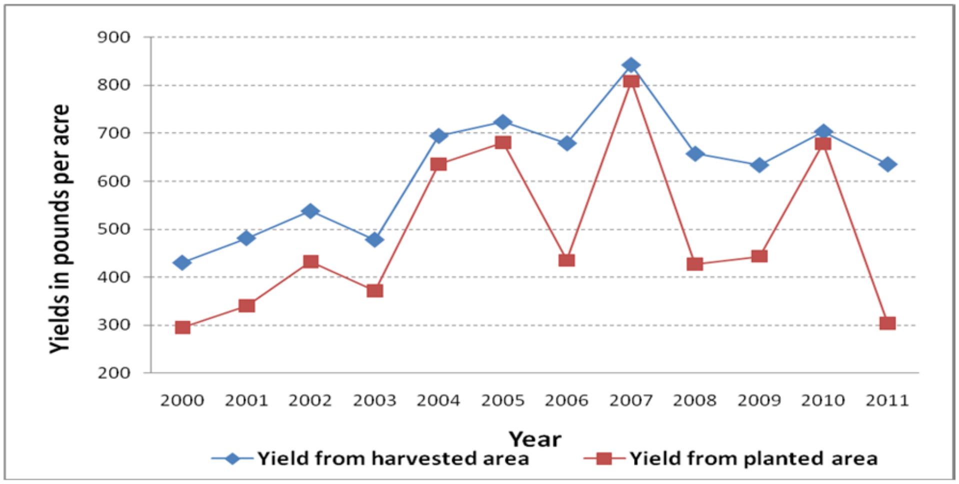

Figure 5. Upland cotton yields calculated as total production in pounds/the planted area in acres and total production in pounds/the harvested area in acres.

CONCLUSIONS

Based on above analysis, we can conclude that satellite remote sensing can be used to monitor the agricultural drought. Among all indices discussed in this paper, it seems that both the VCI and the VHI that combines the VCI and day-time TCI match with USDM drought report very well although the satellite-based monitoring has much higher spatial resolution. The TCI using night-time land surface temperature estimated by the MODIS instrument might contaminates the agricultural drought maps or unrealistically underestimate the severity of the agricultural droughts. Still, further investigation, especially a quantitative one, is required regarding which drought map is the closest to reality. In 3 out of the last 4 years, the Texas state experienced severe to extreme agricultural droughts. The consecutive agricultural drought caused the cotton price to reach an all-time high. More price hikes in the cotton are expected largely due to extreme to exceptional droughts occurring in 2011.

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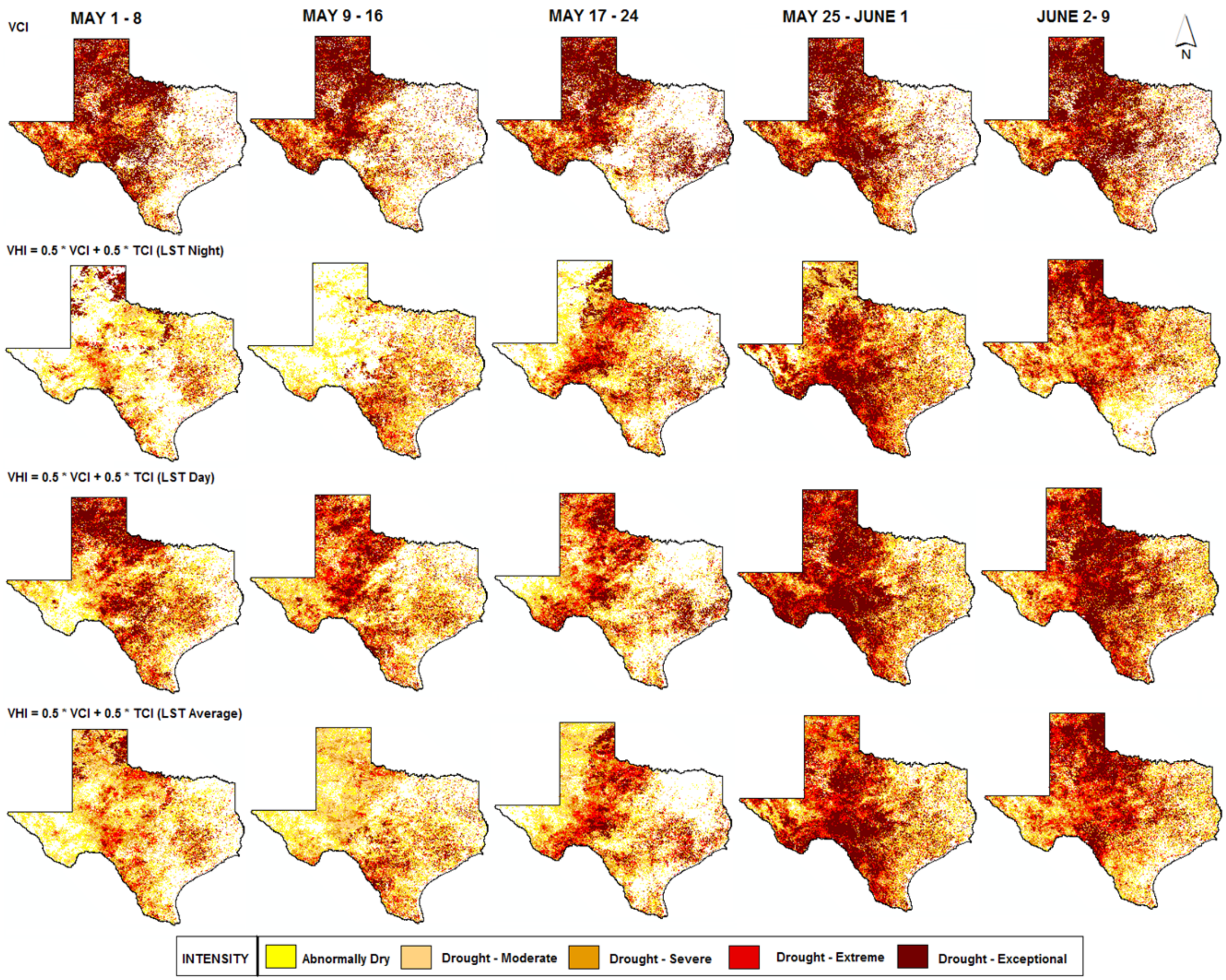

Figure 6. Agricultural Drought maps for the Texas state between May 1 and June 9 2011. The first line points to VCI in, second line points to VHI=0.5*VCI + 0.5*TCI (Night LST), the third line points to VHI=0.5*VCI + 0.5*TCI (Day LST) and the last line points to VHI=0.5*VCI + 0.5*TCI (Average LST).

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