Long-term agricultural performance and climate variability for drought assessment: a regional study from Telangana and Andhra Pradesh states, India

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ABSTRACT
A novel approach is presented to assess the agriculture performance in the states of Telangana and Andhra Pradesh using long-term fortnightly satellite, meteorological and irrigation data-sets. National Oceanic and Atmospheric Administration (NOAA), Global Inventory Modeling and Mapping Studies (GIMMS) and Normalized Difference Vegetation Index (NDVI) data for the period 1982–2000 were used to study the pattern of anomalies in the NDVI anomalies and Standardized Precipitation Index (SPI) in the agriculture areas to capture the drought events. After hierarchical image classification and field observations, the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI product was used to generate the cropped area. The deviation of the NDVI (NDVIDev) was used to understand the agricultural growth/stress, variations in the cropped area and per cent fluctuation in space and time. The SPI, derived from the rainfall data pertaining to 2000–2015, was used to determine the distribution of precipitation. The crop area (%) and growth conditions during the different cropping seasons agree well with the prevailing drought conditions. A significant (p < 0.05) relation was found between the NDVI and precipitation in the summer monsoon each year except during excellent summer monsoon year. The seasonal precipitation, residual soil moisture and source of irrigation were also found to have significant (p < 0.05) impacts on the winter and summer crops.

1. Introduction
Agriculture is one of the major economic activities in India. About two-thirds of India’s population is dependent on agriculture. Hence, any change in the crop conditions/stress is likely to affect the overall economy of the country (Parmeshwar et al. 2014). Over the years, the performance of agriculture in India has improved significantly as witnessed by the ability of agriculture to sustain the area under cultivation and by assessments of growth. Maintenance of area under agriculture, extension of irrigation project, fertilizers and pesticides application have led to the development of better plans to combat drought by creating various irrigation facilities (Parthasarathy 1994). Much of the agriculture in India is dependent on the monsoon, particularly the south-west monsoon (on average, 80% of the annual rainfall occurs between June and September) (Niranjan Kumar et al. 2013). Estimation of regional crop vigour and growth and stress conditions on the basis of intermittent field observations...
is not only expensive but at times prone to large errors. On the other hand, satellite remote sensing systems (National Oceanic and Atmospheric Administration (NOAA), Advanced Very High Resolution Radiometer (AVHRR) and Terra Moderate Resolution Imaging Spectroradiometer (MODIS)) provide data daily, which can be effectively used. Satellite remote sensing technology is being used widely to monitor agriculture and crop growth status in terms of both space and time (Harris 2003; Jeyaseelan 2003; Seelan et al. 2003; Thenkabail et al. 2004; Naresh et al. 2009; Gebrehiwot et al. 2011; Himanshu et al. 2015; Francisco et al. 2016).

Studies have shown that significant changes in land use and phenology occur due to the impact of prolonged drought (Bethany & John 2008). It is well known that drought is one of the major environmental disasters (Maybank et al. 1995). Drought is triggered by deficiency in precipitation over an extended period, a season or longer (American Meteorological Society 2004; Goudie 2013; Pandey et al. 2014). Agricultural drought is most reliably assessed using space-driven data to develop response and mitigation strategies, to assess vulnerability and to develop preparedness plans (Jeyaseelan 2003; Long et al. 2011; Loon 2015). Most of the studies related to agricultural drought in India have been carried out in the kharif season (June–September) (Nataraja & Ram Mohan 2010; Murthy et al. 2011). However, globally, agricultural drought is monitored in conjunction with meteorological and satellite-derived indices, namely deviations in the normalized difference vegetation index (NDVIdex), vegetation condition index (VCI) and standardized precipitation index (SPI) (Patel et al. 2007; Gebrehiwot et al. 2011; Patel et al. 2012; Dutta et al. 2013; Rui et al. 2014; Dutta et al. 2015; Chen et al. 2016; Francisco et al. 2016).

The present study was carried out in the state of Andhra Pradesh (AP) when it was undivided, 34% of its gross domestic product being from the agricultural sector (APSDPS 2014–2015). Recently, Palanisami et al. (2015) have reported that 94% of the area in undivided AP is vulnerable to agricultural drought in the changing climate scenario. Therefore, it becomes important to understand the relationship between the climatic drivers and irrigation sources to determine the crop area (distribution among three cropping seasons, the ratio of cropped area to fallow area, per cent fluctuation of cropped area in different districts) and crop vigour, which in turn indicate the crop growth and drought conditions. The present study uses agriculture performance in terms of area under cropping and growth conditions. These parameters have been studied along with the climate and the irrigation sources.

The research objectives of the present study are the following:

1. To understand the seasonal pattern of NDVI anomalies using NOAA GIMMS (1982–2000) and MODIS NDVI (2000–2015) data-sets along with the SPI (30 years’ rainfall data from the India Meteorological Department (IMD)),
2. To understand the crop growth/stress and drought conditions (all three cropping seasons of the region) using MODIS NDVI and rainfall data relating to 15 years (2000–2015),
3. To understand the relationship between agricultural performance and precipitation and irrigation sources, and
4. To assess the frequency and magnitude of crop stress for agricultural drought analysis using area and crop vigour as surrogates.

2. Study area

The study area encompasses 22 districts of undivided AP in which agriculture is dominant. Hyderabad District is excluded from the present study because it has no significant agricultural area according to the statistics in a report on the state’s agriculture (Vamsi 2004). Undivided AP lies in the tropical region between latitudes 12°14′ N and 19°54′ N and longitudes 76°46′ E and 85°40′ E. The area falls in the semi-arid region of peninsular India and can be broadly divided into two regions, namely, Andhra Pradesh (comprising 13 districts) and Telangana (10 districts), as shown in Figure 1. The three distinct seasons of AP are the kharif or summer monsoon (June–September),
winter or rabi (October–January) and summer or zaid (February–May). The annual maximum temperature of the state is \(\approx 20^\circ C\), while the minimum is around 10–12 \(^\circ C\) (Revadekar et al. 2012). The coastal plains experience warm summers, with temperatures often exceeding \(\approx 38^\circ C\) at places. The south-west monsoon contributes almost two-thirds of the annual rainfall, which, however, varies widely across the state. Some coastal areas receive 1400 mm of rain, whereas the northern and western parts of the plateau receive about 500 mm. Most of the cultivation (around 68.27%) takes place during the monsoon/rainy period from June to September. Other irrigation sources and the residual soil moisture are used for cultivation of crops in winter (rabi, October–January). The moisture stress modulates the crop growth and is reflected in the NDVI. The sowing pattern is also dependent on the precipitation and available soil moisture.
| Seasons | Districts         | Rain fed | Irrigation       | Rain fed | Irrigation       | Vegetable Rain fed | Zaid Irrigation       |
|---------|------------------|----------|------------------|----------|------------------|---------------------|-----------------------|
| Kharif  | Adilabad         | Cotton, pigeonpea, soybean | Rice | Sorghum, chickpea, cowpea | Chillies, tomatoes, bhendi, coriander, brinjal |
|         | Ananthapur      | Groundnut, pigeonpea, sorghum | Rice, groundnut | Sorghum, chickpea, sunflower | Chillies |
|         | Chittoor         | Groundnut, pigeonpea | Rice, groundnut | Rice, groundnut | Chillies |
|         | YSR Kadapa       | Groundnut, sunflower, cotton | Rice | Sunflower, chickpea | Chillies, gourds, bhendi, brinjal |
|         | East Godavari   | Groundnut, pigeonpea | Rice, sugar cane | Rice | Greengram, blackgram |
|         | Guntur           | Cotton, pigeonpea, greengram, pigeonpea | Rice | Blackgram, tobacco | Chillies, tomatoes |
|         | Karimnagar       | Cotton, maize, greengram, pigeonpea | Rice, cotton | Chickpea, sorghum | Chillies |
|         | Khammam          | Groundnut, sunflower, pigeonpea | Rice | Sorgum, horsegram | Chillies, tomatoes |
|         | Krishna          | Maize, castor, rice, sorghum, pigeonpea | Rice | Sorgum, chickpea, safflower | Chillies, tomatoes |
|         | Kurnool          | Rice | Sorgum, horsegram | Maize, rice, groundnut, sunflower | Chillies |
|         | Mahbubnagar      | Maize, sorghum, greengram, cotton, blackgram | Rice | Horsegram, cowpea, pigeonpea | Potato |
|         | Medak            | Cotton, castor, groundnut, pigeonpea | Rice | Blackgram, greengram, sunflower, chickpea | Chillies |
|         | Nalgonda         | Rice, sunflower, groundnut | Rice | Chickpea, sunflower | Tomatoes |
|         | SPSR Nellore     | Rice, maize, sugarcane | Rice | Sorgum, maize, rice | Chillies |
|         | Nizamabad        | Cotton, pigeonpea, greengram, soybean, blackgram, rice | Rice | Maize, sorghum, sunflower | Tomatoes |
|         | Prakasam         | Cotton, maize, pigeonpea, sorghum | Rice | Tobacco, sunflower | Chillies, tomato |
|         | Sriakulam        | Mesta, sesame | Rice, sugar cane | Greengram, horsegram | Chillies |
|         | Vizianagaram     | Mesta, sesame | Rice | Blackgram, greengram, maize, groundnut, rice, horsegram | Chillies |
|         | Warangal         | Cotton, maize, pigeonpea, greengram, groundnut, rice | Rice, maize, cotton, sugarcane, sunflower | Blackgram | Chillies |
|         | West Godavari    | Rice, sugar cane, maize, sesame | Rice, maize, tobacco, groundnut, sunflower, blackgram | Chillies |
2.1. Cropping system

Due to the diversified climatic conditions, landforms and soil types, there are different crops in the three cropping seasons. Farmers harvest crops according to the agro-climatic region and the rainfall pattern of a particular year (Ranuzzi & Srivastava 2012). The net irrigated area (NIA) from the total geographical area in undivided AP is approximately 19% (Agriculture Action Plan 2015–2016). The major crops are rice, grown during the summer monsoon and winter, maize, grown in winter, and vegetables, grown during winter and summer. District-wise details of the crop cultivation in the three seasons are given in Table 1 (compiled from Prasad et al. 2012).

3. Materials and methods

3.1. Data

3.1.1. Satellite data

The present study uses NOAA AVHRR GIMMS data for the period from 1982 to 2000 and Terra MODIS satellite data for the period from 2000 to 2015. The NOAA AVHRR GIMMS NDVI product (8 km × 8 km) was downloaded from http://iridl.ldeo.columbia.edu/SOURCES/.UMD/.GLCF/.GIMMS/.NDVIg/.global/ndvi/downloadsGeoTiff.html. NOAA AVHRR GIMMS NDVI data are derived from the images obtained from the AVHRR instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17. This NDVI data-set has been corrected for calibration, view geometry, volcanic aerosols and other effects that are not related to vegetation change. The data contain global geographical projections (Geographic, WGS 1984). The GIMMS NDVI product is an 8-km resolution, 15-day maximum value composite bimonthly global NDVI product generated from AVHRR data (daac.ornl.gov). The MOD13A2 Vegetation Index products were downloaded from LPDAAC (https://lpdaac.usgs.gov) and processed using appropriate image processing software to derive the NDVI data for the years 2000–2015. The land use and land cover (LULC) maps derived from the LANDSAT data (www.glcf.com) for the year 2005 were used to mask the non-agricultural area, including forests, settlements and barren land. The LULC map of the year 2005 was refined according to the methodology developed by Roy et al. (2015). The map was overlaid with 2000, 2010 and 2015 LANDSAT data to derive the 2000, 2010 and 2015 LULC maps. LULC maps were derived for every five years by appropriately modifying the theme polygon where the changes were observed. The LULC maps of 2000, 2005, 2010 and 2015 were used to identify the agricultural area (cropped and currently fallow) using the maximum area under agriculture during 2000–2015.

3.1.2. Meteorological and water resources data

The daily rainfall data (at 0.25° × 0.25°) available from the IMD for the period 1982–2015 were used in this study (Pai et al. 2014). The surface water (SW), groundwater (GW) and NIA statistics of the state for the period 2000–2011 were downloaded from the websites of the International Crop Research Institute for Semi-arid Tropics and Village Dynamics in South Asia (http://vdsa.icrisat.ac.in/), and the statistics for the period 2012–2015 were downloaded from the website of the Groundwater Planning Department of AP (DACNET).

3.2. Pre-processing of data

3.2.1. NOAA GIMMS NDVI processing

The downloaded NOAA AVHRR GIMMS NDVI data were multiplied by a scale factor of 0.004 (ftp://gimms.gsfc.nasa.gov/MODIS/README.txt) before subset the study area. The bimonthly NDVI products from 1982 to 2000 were stacked in sequence for the three cropping seasons, namely the kharif/summer monsoon (June–September), rabi/winter (October–February) and zaid/summer (February–May). The stacked seasonal NDVI files were then masked out for the non-agricultural areas using the LULC mask prepared from the LANDSAT data. The seasonal agriculture NDVI files
(1982–2000) were used to generate NDVI anomalies using the equation.

\[
\text{NDVIDev} = \frac{X_i - X_m}{C_0} 
\]  

\[ \text{(1)} \]

3.2.2. MODIS NDVI processing
The Terra MODIS NDVI products that were downloaded from the LPDAAC data pool were projected onto the geographic coordinates with the WSG84 datum. The fortnightly NDVI layer was further refined by removing the cloud-covered and other unreliable pixels using the quality flag provided with the NDVI product. The fortnightly NDVI products from 2000 to 2015 were stacked in sequence for the three cropping seasons, namely kharif/summer monsoon (June–September), rabi/winter (October–February) and zaid/summer (February–May). The procedure for masking out the non-agricultural area was as described in Section 3.2.1 to prepare the MODIS agricultural NDVI files. The agricultural area includes the cropped area and the currently fallow land, and it was extracted from the LULC mask. The associated features were extracted from the source LULC maps to provide better visualization.

3.3. Processing of data
3.3.1. Extraction of agricultural/cropped area
The agricultural area masked, NDVI was considered potentially cultivable area. However, due to a lack of rainfall or other reasons, potentially cultivable area is not fully sown every year. Hence, the percentage of cropped and fallow land varies each year. In order to extract the cropped area of each season (during 2000–2015), NDVI thresholds were determined on the basis of sample ground data. The thresholds were used for hierarchical image classification (Bikash 2006; Brian & Egbert 2008) (Figure 2). However, Ananthapur, Kurnool and YSR Kadapa districts (summer monsoon) and Adilabad, Ananthapur, Mahbubnagar, Medak, Nizamabad and Rangareddy districts (winter) were given different thresholds (Table 2) according to ground truth as the cultivated crops vary (Table 1).

The percentage crop areas (CA %) in different cropping seasons during 2000–2015 were generated using the following equation:

\[
\text{CA\%} = \frac{\text{No. of cropped pixel}}{\text{Total no. of agriculture pixels}} \times 100
\]

\[ \text{(2)} \]

The ratio of the cropped area (CAP) to the potential cultivable area in each district was calculated.

\[
\text{CAP} = \frac{\text{Cropped Area}}{\text{Agricultural land}}
\]

\[ \text{(3)} \]

Table 2. NDVI threshold for districts having different cropping pattern for the crop land.

| Districts | Season | Ananthapur | YSR Kadapa | Kurnool | Mahbubnagar | Medak | Nizamabad | Rangareddy |
|-----------|--------|-------------|------------|---------|-------------|-------|-----------|------------|
| SM        | NDVI > 0.327 | NDVI > 0.366 | NDVI > 0.37 | –       | –           | –     | –         | –          |
| W         | NDVI > 0.347 | –           | –          | NDVI > 0.38 | NDVI > 0.44 | NDVI > 0.40 | NDVI > 0.407 |
The crop area (%) fluctuation was (CAF) calculated using the following equation to capture the sensitivity of crop stress due to variability in rainfall.

$$CAF = X_{max} - X_{min}$$

(4)

where $X_{max}$ and $X_{min}$ are the long-term maximum and long-term minimum of the crop area (%).

### 3.4. NDVI anomaly (NDVIDev) and vegetation condition index (VCI)

The vegetation indicators, namely the NDVI anomaly and VCI, provide alternative measures of the relative health of the vegetation. These indices can be used to monitor areas where vegetation may be stressed, as a proxy to detect potential drought. The difference between the average NDVI for a particular fortnight of a given year and the average NDVI for the same fortnight over the last 15 years (MODIS NDVI 2000–2015) is called the NDVI anomaly (Tucker 1979).

In most agro-ecosystems, the growth of vegetation is controlled by the quantity of water available, so the relative density of the vegetation is a good indicator of agricultural drought. The VCI compares the current NDVI with the range of values observed in the same period in previous years and can be expressed (Kogan 1995, 1997) as

$$VCI = \frac{X_i - \text{Max } X_{ij}}{\text{Min } X_{ij} + \text{Max } X_{ij}}$$

(5)

The VCI (expressed in %) gives an idea where the observed value is located in the range between the extreme values (minimum and maximum) of the previous years. Lower and higher values indicate bad and good vegetation states, respectively. The deviation of NDVI (NDVIDev) and VCI were used to assess the vegetation stress and vegetation growth conditions. A strong correlation ($R^2 = 0.98$) was found between the NDVI (NDVIDev) and VCI.

The per cent NDVI deviation was derived from the following equation for the agricultural area to assess the frequency of stress at the state and district levels:

$$\text{NDVIDev Percentage} = \frac{\text{No. of Negative NDVIDev pixels}}{\text{Total No. of pixel}} \times 100$$

(6)

Frequency NDVIDev Percentage = No. of years $\text{NDVIDev Percentage} > 50%$

(7)

The temporal and spatial extremities of agricultural performance were measured by aggregating the frequency of CAF and the frequency of NDVIDev (percentage).

### 3.5. Standardized precipitation index (SPI)

The SPI is a normalized index representing the probability of occurrence of the observed rainfall at a certain geographical location compared with the rainfall at that location over a long-term reference period. Negative SPI values represent deficits in rainfall, whereas positive values indicate surplus rainfall. The daily gridded data were converted into seasonal data for the three seasons using the GrADS and ERDAS software packages. The seasonal rainfall data were used to derive the SPI using the equation (McKee et al. 1993)

$$\text{SPI} = \frac{X_i - X_m}{\sigma}$$

(8)
The main advantage of the SPI is that it can be compared across regions in different climatic zones. The gridded daily rainfall data of the IMD (0.25° × 0.25°) for the period from 1982 to 2015 (>30 years) were used to derive the SPI of the study area.

The NDVI, VCI and NDVIDev at the state and district levels were statically analysed using the R software package (http://openwetware.org/wiki/R_Statistics). The relation between the mean NDVI and the rainfall, SW, GW and NIA was determined using simple and multiple linear regressions, and confidence level (p and t values). The overall methodology of this study is illustrated in Figure 3(a,b).

Figure 3. Schematic diagram describing the methodology of (a) NOAA AVHRR GIMMS NDVI; and (b) MODIS NDVI.

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4. Results and discussion

The primary requirements for agriculture are water, soil, nutrition and management practices. However, in many cases, the proportions of these inputs vary, depending upon the amount of precipitation the region has received, the availability of irrigation and the management of the nutrition and other cultural practices (FAO 2003). The NDVI and VCI follow similar patterns across the seasons and years in the present study. The NDVIDev varies considerably and captures the stress in cropped areas. However, the VCI captures only the severely drought-affected years. Hence, the present study uses the NDVI and the anomalies associated with it (NDVIDev). The precipitation and irrigation sources (SW and GW) and their impacts on the agricultural crops have been used to determine drought events and their spatial and temporal variability during 2000–2015.

4.1. Seasonal pattern of NOAA AVHRR NDVI anomaly and SPI

The long-term (1982–2000) seasonal patterns of the GIMMS NDVI anomaly and SPI are shown in Figure 4(a). During the summer monsoon, the deviation of the NDVI closely follows the pattern of the corresponding SPI except during 1999–2000, where an abrupt raise in the NDVI is noticed from August to September (Figure 4(b)) because of the impact of rainfall. During winter and summer, the NDVIDev follows the pattern of monsoons SPI (summer monsoon and winter).

4.2. Crop area and proportions

The crop area percentages for the three cropping seasons starting from 2000–2001 to 2014–2015 are presented in Figure 5(a,b). It can be seen from Figure 5(a) that the minimum crop area percentages

![Figure 4](image-url)

Figure 4. (a) Seasonal pattern of NDVIDev and SPI during 1982–2000 years (SPI based on 30 years rainfall data-sets); and (b) June–September monthly profile of NDVI and rainfall during 1999–2000 years.

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were during the summer monsoon and winter cropping seasons in 2001–2002. The second least cropped area percentages were recorded during the winter monsoon in 2008–2009 and during the summer monsoon in 2009–2010. The highest cropped area percentage was recorded during all the cropping seasons of 2010–2011. Furthermore, it can be observed from Figure 5(a) that the increases and decreases in crop area were synchronous with the amount of rainfall received during the south-west monsoon in a year. It is a known fact that during a good monsoon year a larger proportion of the potential agricultural area will be cultivated and during a poor monsoon year a larger proportion of agricultural area will be left fallow. The district-wise proportions of cropped and fallow areas were calculated (as explained in Section 3.3) to determine the impacts of the south-west monsoon and the resulting residual soil moisture. The ratios of the seasonal cropped area to the total agricultural area at the district level are shown in Figure 6(a–c). It can be observed that during the summer monsoon cropping season, the long-term average proportion of cropped area to fallow land was least in Kurnool District, followed by Prakasam District. The highest crop proportions were observed in the coastal districts of Andhra, namely Srikakulam, Vizianagaram, Visakhapatnam and East Godavari districts. During the winter cropping season, Prakasam district again had the lowest proportions of long-term average crop area, and the maximum was in Khammam and Warangal districts. During the summer cropping season, Ananthapur, Mahbubnagar and Rangareddy districts had the least crop proportions, and West Godavari district had the highest proportion of cropped area in all the three cropping seasons. The aforesaid assessment provides us an understanding of the proportions of cropped and fallow areas during the study period.

The analysis of the cropped area during the assessment period has revealed noticeable fluctuations between the years. The maximum observed fluctuation at the state level is 35%, during the summer monsoon, followed by summer (26%) and winter (25%). These fluctuations are primarily
due to the variation in precipitation and availability of soil moisture (Komuscu 1999; Kang et al. 2009; Alam et al. 2011). These results are also supported by the correlation analysis and multiple regression (Table 3). The fluctuation in the cropped area differs from district to district due to the changes in precipitation, available soil moisture, cropping system and market scenario. During the summer monsoon, the maximum fluctuation in area was observed in SPSR Nellore District, followed by Prakasam District. In winter, Mahbubnagar, Kurnool and Prakasam districts had the maximum fluctuations, followed by Karimnagar District. During summer, the maximum fluctuation was in Vizianagaram District (Figure 7).

4.2.1. Seasonal patterns of deviation of the NDVI and SPI

The seasonal patterns in the deviation of the NDVI and SPI are shown in Figure 8(a). The pattern of deviation of the NDVI is synchronous with that of the SPI during the summer monsoon months. However, it was observed that a negative SPI during the monsoon cropping season results in a negative deviation in the NDVI in both the winter and summer cropping seasons during a particular cropping year. The only exception was 2001–2002, when the summer monsoon failed but the state had received a good winter monsoon, and thus a good winter crop was produced. This pattern clearly emphasizes that the summer monsoon rain and the resulting residual soil moisture have a major role to play on the winter and summer cropping seasons.

Figure 8(b) shows the NDVI profiles of a good monsoon year (2010–2011) and stress years (2001–2002 and 2002–2003) and the NDVI average of 15 years (2000–2015). It can be observed that during the summer cropping season the NDVI attains its maximum value during the months of September and October. The NDVI profile is below average during the summer monsoon in 2001–2002. During the winter following the summer in 2002–2003, the NDVI is minimum. The NDVI is above average during all three seasons in 2010–2011.

4.3. Relation between NDVI and precipitation and water resources

4.3.1. State level

Figure 8(a) clearly shows a one-to-one correspondence between the summer monsoon SPI and the summer monsoon cropping season NDVI deviation, whereas the winter crop deviation was more...
related to the summer monsoon SPI and the resulting residual soil moisture. Simple and multiple linear regression analyses were carried out between the seasonal NDVI and the monsoon rainfall, NIA, SW and GW to verify this hypothesis. The coefficient of determination ($R^2$) of the relation between the NDVI and the rainfall, NIA, surface and GW for the state of AP is presented in Table 3.

During the monsoon, the state NDVI showed a 95% ($p < 0.05$) significant relation with the summer monsoon rainfall in most of the years, except 2001–2002 (extreme dry year). The strongest relation was observed during 2006–2007 and 2003–2004. There was no significant relation during 2010–2011 because there was excess rainfall in 2010. It is a known fact that the NDVI saturates after a certain amount of rainfall, beyond which there is no significant change in the NDVI.

When the winter cropping season NDVI was regressed on the water sources such as the monsoon rainfall, winter rainfall, NIA, SW and GW, it was observed that there are significant relations

### Table 3. Yearly seasonal relation of NDVI vs. rainfall and water resources.

| Years       | Monsoon $R^2$ | Remarks          | Winter $R^2$ | Remarks Multiple regression | Summer $R^2$ | Remarks Multiple regression |
|-------------|---------------|------------------|--------------|------------------------------|--------------|------------------------------|
| 2000–2001   | 0.23          | MNDVI vs. MR     | 0.23         | WNDVI vs. MR and WR         | 0.50         | SNDVI vs. annual total rain and NIA |
| 2001–2002   | 0.16**        | MNDVI vs. MR and NIA | 0.26*        | WNDVI vs. MR and WR         | 0.40*        |                             |
| 2002–2003   | 0.49*         | MNDVI vs. MR     | 0.37*        | WNDVI vs. MR and WR         | 0.46*        |                             |
| 2003–2004   | 0.65*         |                  | 0.65*        | WNDVI vs. MR and SW         | 0.81*        |                             |
| 2004–2005   | 0.47*         |                  | 0.34*        | WNDVI vs. MR and WR         | 0.64*        |                             |
| 2005–2006   | 0.41*         |                  | 0.41*        | WNDVI vs. MR and SW         | 0.54*        |                             |
| 2006–2007   | 0.70*         |                  | 0.73*        | WNDVI vs. MR and SW         | 0.82*        |                             |
| 2007–2008   | 0.27*         |                  | 0.32*        | WNDVI vs. MR and SW         | 0.56*        |                             |
| 2008–2009   | 0.19*         |                  | 0.27*        | WNDVI vs. MR and SW         | 0.49*        |                             |
| 2009–2010   | 0.49*         |                  | 0.23**       | WNDVI vs. MR and WR         | 0.49*        |                             |
| 2010–2011   | –             |                  | 0.32*        | WNDVI vs. MR and SW         | 0.49*        |                             |
| 2011–2012   | 0.56*         | MNDVI vs. MR     | 0.43*        | WNDVI vs. MR and SW         | 0.57*        |                             |
| 2012–2013   | 0.51*         |                  | 0.75*        | WNDVI vs. MR and SW         | 0.85*        |                             |
| 2013–2014   | 0.45*         |                  | 0.55*        | WNDVI vs. MR and SW         | 0.54*        |                             |
| 2014–2015   | 0.33*         |                  | 0.46*        | WNDVI vs. MR and SW         | 0.85*        |                             |

Note: MNDVI: monsoon NDVI; WNDVI: winter NDVI; SNDVI: summer NDVI; MR: monsoon rain; WR: winter rain; SW: surface water; NIA: net irrigated area.

*95% confidence level ($p < 0.05$).
**90% confidence level ($p < 0.10$).
between the winter crops NDVI and the monsoon rainfall and winter rainfall. The strongest relation is observed during 2012–2013 and 2006–2007. During 2002–2003, 2008–2009 and 2011–2012 (drought years), the NDVI relations with monsoon and winter rainfall and SW were significant. During summer, the NDVI had significant relations with the total annual precipitation and NIA due to the assured irrigation and residual soil moisture (resulting from the annual rainfall). It is clear from the analysis that the performances of the winter and summer crops depend on the performance of the summer monsoon rainfall, which results in residual soil moisture and SW and GW resources. The significant correlations ($R^2$, with $p < 0.05$) were the following: during the summer monsoon, the highest $R^2$ value (0.70) was in 2006–2007 and the lowest in 2008–2009 (0.19); during winter, the highest $R^2$ value (0.75) was in 2012–2013 and the lowest in 2000–2001 (0.23); during summer, the annual total rainfall and NIA had the highest $R^2$ value (0.85) in 2012–2013 and the lowest in 2001–2002 (0.40).

4.3.2. District level
The state of AP comprises 22 districts with a varied spatial and temporal rainfall distribution. A different cropping system may not reflect the actual relation of the NDVI with the rainfall and other sources of water. Hence, simple and multiple linear regression of the NDVI on the seasonal rainfall and other water resources were carried out for the period from 2000–2001 to 2014–2015. Table 4 shows the district-wise relation of NDVI with the rainfall and water resources. During the summer monsoon cropping season, a significant relation (with $p < 0.05$) was observed between the NDVI
and the rainfall. The strongest relation was noticed in West Godavari District \( (R^2 = 0.87) \), whereas the lowest was in Medak District \( (R^2 = 0.25) \). Further, it must be noted that during the summer cropping season, a significant relation was observed only with the summer rainfall. During the winter cropping season, a significant relation was observed between the NDVI and the monsoon and winter rainfall in most of the districts except Guntur, Karimnagar, SPSR Nellore, Nizamabad, Warangal and West Godavari districts (but there were significant relations when the SW sources were included). The strongest relation was observed in Karimnagar District \( (R^2 = 0.86) \), while the weakest one was observed in Prakasam and East Godavari districts \( (R^2 = 0.32) \). Significant relations \( (p < 0.05) \) were observed with the annual rainfall and NIA during summer, with the highest \( R^2 \) value \( (0.91) \) being in East Godavari District and the lowest value in Srikakulam District \( (0.50) \).

In short, the analysis emphasizes that the cropping in all the years in winter and summer (at both the state and district levels) had a direct bearing on the summer monsoon rainfall and the residual soil moisture resulting from the summer monsoon and winter/summer precipitation during the respective seasons, including the available water resources (NIA and SW) (Krishna Kumar et al. 2004).

4.4. Frequency and magnitude of crop stress/drought analysis

4.4.1. State level

The frequency was assessed by providing the threshold value \( (>50\%) \) of the negative NDVI\(_{Dev}\) of the total agricultural area (Table 5a). In order to assess the magnitude, the level of NDVI\(_{Dev}\) was used (Figure 8(a)). During the summer monsoon, frequent occurrence of negative percentages was

### Table 4. District-wise relation of NDVI vs. rainfall and water resources.

| Districts | Monsoon \( R^2 \) | Remarks | Winter \( R^2 \) | Remarks Multiple regression | Summer \( R^2 \) | Remarks Multiple regression |
|-----------|------------------|---------|-----------------|-----------------------------|-----------------|-----------------------------|
| Adilabad  | 0.32*            | MNDVI vs. MR | 0.51*           | WNDVI vs. MR and WR         | 0.53*           | SNDVI vs. annual total rain and NIA |
| Ananthapur | 0.49*            |         | 0.75*           |                             | 0.53*           |                             |
| Chittoor  | 0.72*            |         | 0.41*           |                             | 0.73*           |                             |
| YSR Kadapa | 0.58*            |         | 0.63*           |                             | 0.73*           |                             |
| East Godavari | 0.33*      |         | 0.32*           |                             | 0.91*           |                             |
| Guntur     | 0.41*            |         | 0.52*           | WNDVI vs. MR, WR and SW     | 0.60*           |                             |
| Karimnagar | 0.33*            |         | 0.86*           |                             | 0.71*           |                             |
| Khammam   | 0.76*            |         | 0.63*           | WNDVI vs. MR and WR         | 0.64*           |                             |
| Krishna    | 0.38*            |         | 0.51*           |                             | 0.52*           |                             |
| Kurnool    | 0.43*            |         | 0.44*           |                             | 0.64*           |                             |
| Mahbubnagar | 0.33*           |         | 0.68*           |                             | 0.69*           |                             |
| Medak      | 0.25*            |         | 0.55*           |                             | 0.71*           |                             |
| Nalgonda   | 0.69*            |         | 0.64*           |                             | 0.69*           |                             |
| SPSR Nellore | 0.71*       |         | 0.55*           | WNDVI vs. MR, WR and SW     | 0.57*           |                             |
| Nizamabad  | 0.56*            |         | 0.69*           |                             | 0.51*           |                             |
| Prakasam   | 0.51*            |         | 0.32*           | WNDVI vs. MR and WR         | 0.71*           |                             |
| Rangareddy | 0.26*            |         | 0.68*           | WNDVI vs. MR and WR         | 0.55*           |                             |
| Srikakulam | 0.53*            |         | 0.43*           |                             | 0.50*           |                             |
| Visakhapatnam | 0.72*       |         | 0.55*           |                             | 0.83*           |                             |
| Vizianagaram | 0.65*         |         | 0.61*           |                             | 0.82*           |                             |
| Warangal   | 0.71*            |         | 0.75*           |                             | 0.86*           |                             |
| West Godavari | 0.87*        |         | 0.64*           | WNDVI vs. MR, WR and SW     | 0.64*           |                             |

Note: MNDVI: Monsoon NDVI; WNDVI: winter NDVI; SNDVI: summer NDVI; MR: monsoon rain; WR: winter rain; SW: surface water; NIA: net irrigated area.

\*95% confidence level \( (p < 0.05) \).
\**90% confidence level \( (p < 0.10) \).
observed in 2001–2002 and 2002–2003, followed by 2008–2009 and 2009–2010, due to low seasonal monsoon precipitation. The results lead to a stress in the growth conditions in the cropped areas (Siderius et al. 2016) and have been used extensively to assess drought conditions (Gautam 2014). The impact of low precipitation in the summer monsoon season on the following winter crops is observed in 2000–2001, 2002–2003 and 2011–2012, followed by 2004–2005 and 2008–2009. The most frequent occurrence was during the summer seasons of 2000–2001 and 2004–2005, followed by 2002–2003 and 2011–2012. The two parameters, total crop area fluctuation (%) and annual NDVIDev, were aggregated to assess the extremities of drought during 2000–2015. The results indicate that 2002–2003 was the extreme drought, followed by 2008–2009.

The magnitude was measured using the level of NDVIDev (Figure 8(a)). During the monsoon season, the largest negative NDVIDev value was observed during 2001–2002, followed by 2009–2010. The highest negative NDVIDev value during winter was observed in 2002–2003, followed by 2011–2012. The results highlight the fact that drought not only influences the cropped area but also the magnitude of the NDVIDev, indicating stress (Figure 9).

Table 5a. Frequency percentage frequency of negative NDVIDev (>50%) from total agricultural area during 2000–2015.

| Years   | SM > 50% | W > 50% | S > 50% | Annual | CAF | Sum NDVIDev and CAF |
|---------|----------|---------|---------|--------|-----|---------------------|
| 2000–2001 | 5        | 20      | 22      | 47     | 1   | 48                  |
| 2001–2002 | 22       | 3       | 15      | 40     | 3   | 43                  |
| 2002–2003 | 22       | 20      | 21      | 63     | 2   | 65                  |
| 2003–2004 | 13       | 6       | 14      | 33     | 1   | 34                  |
| 2004–2005 | 6        | 18      | 22      | 46     | 1   | 47                  |
| 2005–2006 | 17       | 6       | 1       | 24     | 1   | 25                  |
| 2006–2007 | 8        | 11      | 13      | 32     | 1   | 33                  |
| 2007–2008 | 1        | 13      | 0       | 14     | 1   | 15                  |
| 2008–2009 | 21       | 18      | 17      | 56     | 3   | 59                  |
| 2009–2010 | 20       | 12      | 13      | 45     | 3   | 48                  |
| 2010–2011 | 0        | 2       | 0       | 2      | 0   | 2                   |
| 2011–2012 | 5        | 20      | 19      | 44     | 2   | 46                  |
| 2012–2013 | 3        | 4       | 9       | 16     | 0   | 16                  |
| 2013–2014 | 3        | 2       | 2       | 7      | 0   | 7                   |
| 2014–2015 | 11       | 13      | 6       | 30     | 1   | 31                  |

Note: SM: summer monsoon; W: winter; S: summer; CAF: crop area fluctuation.

Table 5b. Spatial percentage frequency of negative NDVIDev (>50%) from total agricultural area.

| District    | SM > 50% | W > 50% | S > 50% | Annual | Annual CAF > 60% | Sum of CAF and NDVIDev |
|-------------|----------|---------|---------|--------|------------------|------------------------|
| Adilabad    | 9        | 12      | 5       | 26     | 0                | 26                     |
| Ananthapur  | 7        | 8       | 8       | 23     | 1                | 24                     |
| Chittoor    | 8        | 7       | 8       | 23     | 1                | 24                     |
| YSR Kadapa  | 8        | 9       | 9       | 26     | 1                | 27                     |
| East Godavari | 5      | 9       | 7       | 21     | 0                | 21                     |
| Guntur      | 8        | 8       | 8       | 24     | 2                | 26                     |
| Karimnagar  | 8        | 7       | 7       | 22     | 1                | 23                     |
| Khammam     | 6        | 8       | 8       | 22     | 1                | 23                     |
| Krishna     | 6        | 8       | 7       | 21     | 1                | 22                     |
| Kurnool     | 8        | 7       | 8       | 23     | 1                | 24                     |
| Mahbubnagar | 7        | 7       | 9       | 23     | 2                | 25                     |
| Medak       | 6        | 8       | 9       | 23     | 0                | 23                     |
| Nalgonda    | 7        | 9       | 10      | 26     | 1                | 27                     |
| SPSR Nellore | 9       | 9       | 8       | 26     | 1                | 27                     |
| Nizamabad   | 6        | 7       | 9       | 22     | 0                | 22                     |
| Prakasam    | 8        | 7       | 8       | 23     | 2                | 25                     |
| Rangareddy  | 9        | 9       | 9       | 27     | 0                | 27                     |
| Srikakulam  | 6        | 6       | 8       | 20     | 1                | 21                     |
| Visakapatnam | 6        | 6       | 7       | 19     | 0                | 19                     |
| Vizianagaram | 8        | 6       | 7       | 21     | 1                | 22                     |
| 2009–2010   | 6        | 8       | 7       | 21     | 1                | 22                     |
| West Godavari | 6   | 9       | 8       | 23     | 0                | 23                     |
Figure 9. Spatial and temporal distribution of extreme and severe dry, and normal and extreme good crop area years during 2000–2015 (a) summer monsoon; (b) winter and (c) summer season.
4.4.2. District level

The district-level frequency is presented in Table 5b. During the summer monsoon, Adilabad, SPSR Nellore and Rangareddy districts have frequent occurrences of negative percentages of \( \text{NDVI}_{\text{Dev}} \). During the winter crop, there are frequent occurrences of negative \( \text{NDVI}_{\text{Dev}} \) values in Adilabad District, and during the summer crop there are frequent occurrences in Nalgonda District. The results indicate that these districts were drought-prone in different cropping seasons during the period of assessment (2000–2015).

The greatest fluctuations in all three seasons in the cropped area during the period of assessment were in Nalgonda, Prakasam, Guntur and SPSR Nellore districts. These fluctuations indicate the factors determining the sensitivity of drought vulnerability. The study concludes that the factors contributing to the fluctuation of the crop area also need to be identified for vulnerability and risk analysis. Besides the precipitation, irrigation facilities and residual soil moisture (type of soil), the socio-economic and market factors need to be considered. The extreme drought-prone districts are YSR Kadapa, Nalgonda, SPSR Nellore and Rangareddy (Table 5b).

5. Conclusion

The study highlights the long-term (1982–2015) inter-annual variation in the \( \text{NDVI}_{\text{Dev}} \), SPI and cropped areas (2000–2015). The results clearly demonstrate that spatio-temporal variation of precipitation and residual moisture are the determining factors of the crop area, growth and stress. The results conclude that rainfall and water availability are the main drivers of agricultural performance. Most of Telangana and Andhra receives the highest rainfall during the summer monsoon, which also has an impact on the winter and summer crops. A small region of the southern districts, namely SPSR Nellore, Prakasam and YSR Kadapa districts, also receives rainfall from the north-east monsoon. This is evident from the large amount of rainfall received during 2010–2011 due to Cyclone Jal. Hence, to assess the vulnerability of the region, it is essential to use the satellite-derived indices (\( \text{NDVI}_{\text{Dev}} \)), the cropped area and its fluctuation, the preceding year’s seasonal precipitation and the sources of irrigation.

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