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Detection of drought events using combination of satellite data and soil moisture modelling

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Abstract

The use of satellite data offers a potentially well usable tool to accurate drought monitoring. The study examines the space-time possibility of agricultural drought detection using freely available data from the MODIS instrument onboard Terra and Aqua satellites that reflects vegetation condition. Vegetation greenness metrics used in this study are based on the spectral reflectance curves in the visible red and near-infrared part of the spectrum and are expressed in relation to the average for the period of 2000-2014. The results are presented in weekly time step for the whole area of the Czech Republic, and are compared to the drought monitor system, based on the SoilClim dynamic model for soil water content estimates. These data, as well as other parameters, such as soil properties and land use, are integrated at 500 meters spatial resolution.

Key words

Drought monitor, remote sensing, MODIS, NDVI, seasonal greenness

Introduction

Remote sensing (RS) technology (observations of the earth surface from sensor systems mounted on air borne, space borne or land-based platforms) is increasingly used for monitoring crops and to detect the impacts of stress on vegetation. The cause of this stress may lie in various biotic (pests, diseases) and abiotic factors. Agricultural drought (and its impacts on vegetation) was analyzed in this study. The efficiency of RS techniques can be seen in the vegetation state metrics calculation, referred as vegetation/drought indices, as well as in large amount of data availability at a time with extensive geographic coverage and high repetition rate. Furthermore satellite images from active sensor MODIS (Moderate Resolution Imaging Spectroradiometer), which is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites, acquiring data in 36 spectral bands, or groups of wavelengths are available for free.

Various vegetation indices (VI) are commonly used for monitoring the vitality and photosynthetic activity of the vegetation, e. g. the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), the Vegetation Condition Index (VCI), the Normalized Difference Water Index (NDWI). They are used to identify the health status of vegetation, to depict phenological changes, to estimate green biomass and also to assess the impact of drought. Drought indices are being used to characterize drought operatively and they vary by the use of disciplinary data. Combining them with remote sensing derived land surface information is typical for the latest generation of drought indices, such as the recently developed Vegetation Drought Response Index (VegDRI; Brown et al., 2008).

The most often deployed vegetation index in many applications is NDVI because of its simplicity in both calculation and interpretation. It has been extensively used for drought monitoring (e.g. Yuhas, Scuderi 2009, Geng et al. 2014), drought detection related to crop yield estimation or forecast (i.e. Liang, 2004, Doraiswamy et al., 2004; Li et al., 2007; Huang et al., 2013; Kowalik et al., 2014). Time series of NDVI allows monitoring not only drought but the natural dynamic of vegetation phenology too (Hmimina et al., 2013).

The vegetation reflects high in the near infrared (NIR = 0.7-1.1 μm) due to its canopy geometry, the health of the standing vegetation and absorbs more in the red (RED, around 0.66 μm) radiation range due to its biomass and photosynthetic activity. Stressed vegetation has a higher reflectance than a healthy vegetation in RED and lower reflectance in NIR radiation range of the electromagnetic spectrum. Vegetation indices take the advantage of this differential response in the visible and the infrared range of the spectrum and indicate both changes in cellular structure of the leaves and the amount of chlorophyll present in the plants.

The main objective of this paper is to evaluate detected drought events using remotely sensed NDVI. It is hard to differentiate between vegetation anomalies caused by drought and changes caused by other stress factors without further information. The close relationship between vegetation vigour and available soil moisture means that the MODIS-acquired NDVI could be used to evaluate drought events by comparing it to outputs of Integrated Drought Monitoring System (IDMS, Trnka et al, 2014). This IDMS is based on the actual meteorological measurements in addition with another input data, such as soil types, land cover, slope and amount, extent and duration of snow cover, and is capable to assess the drought occurrence and its severity in a daily step.

Materials and methods

1) Satellite-based vegetation stress monitoring

For the satellite data set, measurements collected by MODIS instrument aboard Terra satellite for almost 15 years (from Feb. 2000 to Jul. 2014) were used. As indicator of vegetation health condition NDVI (eqv.1) was used. It is a function of green leaf area and biomass and it consists of a normalized ratio of the NIR and red bands (RED):

$$NDVI = (NIR - RED) / (NIR + RED) \qquad (1)$$

The MODIS Surface Reflectance daily product at 250-meter resolution for the period 2000-2014 was obtained through the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota. This tool provides Bands 1 and 2 (centered at 648 nm, and 858 nm, respectively) that were used to calculate NDVI. Using associated data quality layer pixels of lower quality mainly due to clouds were masked. The cause of variations or noise in radiometric data can be either by instrument calibration, scan angle, sun angle or atmospheric conditions. The effect of noise can be reduced by data composition using the greenest pixel method or via data smoothing with curve fitting of filtering techniques. In order to eliminate high-frequency noise of channel values, the NDVI was calculated and smoothened using filtering procedure developed by Mendel University in Brno and Global Change Research Center AS CR, v. v. i. in cooperation with National Drought Mitigation Center and Center for Advanced Land Management Information Technologies, both University of Nebraska-Lincoln.

Due to variation in NDVI time series, caused by utilization of crop rotation schemes and changing crop patterns between seasons, the NDVI values were aggregated into a rectangular grid with cells of size 5 x 5 km; i. e. the average value of all pixels inside a cell represents the cell value. For each cell, the prevailing type of land cover was determined using Corine Land Cover 2006 data set – Version 16 (04/2012). Then reclassification of all vegetation categories into 7 main categories on the dataset was carried out with exclusion of artificial surfaces, water bodies and wetlands: (1) arable land, (2) heterogeneous agricultural areas, (3) grassland and pastures, (4) broad-leaved forest, (5) coniferous forest, (6) mixed forest, (7) scrub and/or herbaceous vegetation associations and/or bare areas.

The severity of drought situation could be assessed by the extent of NDVI deviation from its historical mean. The concept of relative greenness was used in next steps starting with the calculation of average NDVI values in a weekly step for the period 2000-2014. The difference of the average value from the long term mean for a particular week is referred as Percent of Average Actual

Greenness (PAAG, Fig. 1). In order to depict drought impacts especially on field crops, two variations of this parameter were obtained by taken different landuse category range into account.

2) Ground based drought monitoring tool

The SoilClim model (Hlavinka et al. 2011) based on approach by Allen et all. (1998), was used as a tool for estimation of reference and actual evapotranspiration, presence of snow cover, soil temperature at 0.5 m depth and soil moisture course within two defined layers. SoilClim works in a daily time steps and needs maximum and minimum air temperature, global solar radiation, precipitation, vapor pressure and wind speed as meteorological inputs. Further datasets for simulation are required, such as the basic soil properties (soil water holding capacity) and information about vegetation cover that is defined by coefficients of crop identification, referred as Kc parameters.
This tool was used for the whole area of the Czech Republic divided into regular grids with spatial resolution 500 m. The rendered maps of drought intensity compares the actual value of soil moisture in each grid for a particular day with the distribution of soil moisture values during the period 1961 – 2010 with time window of ± 10 days from current date. The value is subsequently expressed as a percentile of soil moisture in a specific day and is used to assign the corresponding category of drought intensity (S0 – S5) to it.

Results

NDVI as a function of green leaf area and biomass is successfully used index for operational drought assessment. Mainly the relative greenness approach, i.e. the ration of current NDVI to the historic mean NDVI for the same region and period give us the information about impacts of stress on vegetation. The greenness parameter PAAG is visualized in Fig 1 for the week 28 in 2014 for the Czech Republic at 5 km spatial resolution reflecting the vegetation condition after prolonged low rainfall time period: the bigger map depicts relative greenness by averaging NDVI values for cropland and grassland pixels exclusively; the change compared to the situation of the previous week is mapped on the left bottom side; vegetation greenness using NDVI values for all land cover types is illustrated on the left top map.

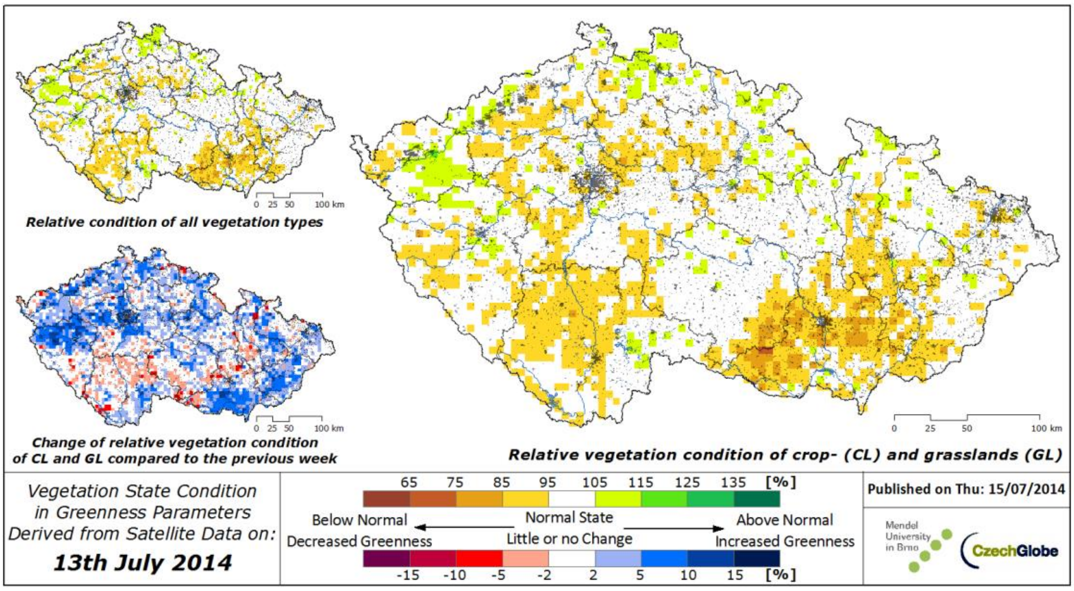

Fig. 1: Percent of average actual greenness (PAAG), the NDVI-derived landuse specific greenness parameter that reflects relative vegetation condition for a particular week from Sunday, 06th July to Sunday, 13th July 2014.

Consequently the results assessing the relative vegetation condition and the intensity of drought for the time period between weeks 12 and 26 in 2012 have been compared using GIS technique. Prolonged and intense drought event in the southern and central Moravian region (partially apparent in the Bohemian region) is evident in maps of drought intensity (Fig. 2a) based on outputs from IDMS. This situation had a negative impact on vegetation especially at a time of intense spring growth (between weeks 21 - 23). This could be observed from satellite images as well, namely from the greenness parameters, that are being derived from satellite data and reflect the relative condition of vegetation (Fig 2b). The strongest negative response of the vegetation in week 22 can be associated with the decreased water availability within the root-zone soil layer in the course of the actual and the previous week.

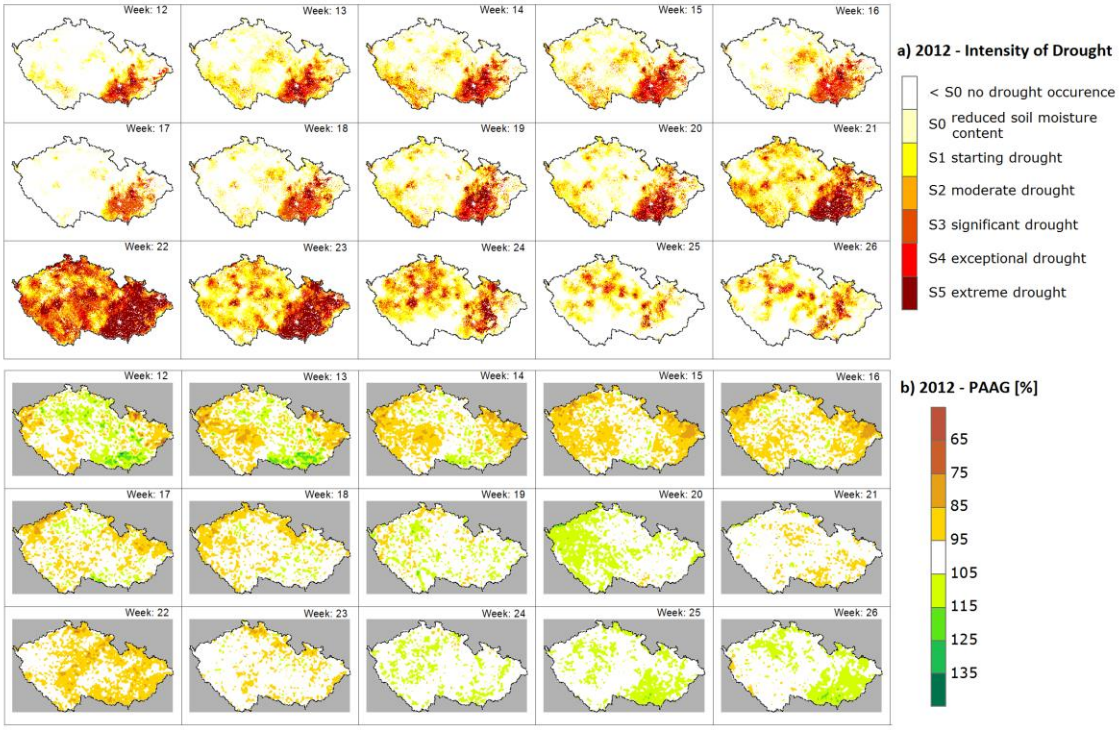

Fig. 2: The visualization of a) the intensity of drought within the root-zone soil layer for the period between weeks 12 and 26 in 2012, b) percent of average actual greenness (PAAG), the NDVI-derived greenness parameter that reflects relative condition of all vegetation types, for the same period.

The sensitivity of the method was verified in the study by evaluating the relative vegetation condition based on NDVI in the whole area of the Czech Republic. The weekly data accessibility is a big advantage highlighted by the independence of this method on ground measurements and observations. The obtained results confirm that this satellite approach is valuable additional tool for basic ground method assessing the agricultural drought.

Conclusion

The change in absorption and reflection characteristics could the underlying idea for a tool monitoring various cause stressed vegetation. NDVI is one of VIs indicating given changes of spectral characteristics. Its original values or derived parameters give us the information if and how much stress the plants are under. In case of drought events detected using meteorological data and further information (about soil, exposition, snow cover etc.) NDVI can be used for vegetation water stress confirmation. The example of the year 2012 with significant episode of spring drought, indicated by drought monitoring based on SoilClim, justifies the use of this method for the determination of drought and its impacts on vegetation.

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Summary

Článek je příspěvkem k problematice monitoringu zemědělského (půdního) sucha využívající technologie dálkového průzkumu Země pomocí satelitů. Senzorem MODIS (Moderate Resolution Imaging Spectroradiometer) umístěným na družici Terra byla v týdenním kroku sledována kondice vegetace prostřednictvím parametrů, odvozených z vegetačního indexu NDVI (Normalized Difference Vegetation Index). Data byla agregována pro celé území České republiky v gridu 5x5 km, aby byl získán reprezentativně homogenní obraz krajiny a jejího landuse. Změny a anomálie v hodnotách indexu směrem ke zhoršení kondice vegetace naznačují působení stresu. V případě časové shody takto pozorovaného stresu s vyšší intenzitou sucha, kterou ukazuje ISSS (Integrovaný Systém Sledování Sucha) založený na pozemních datech, lze s vysokou mírou pravděpodobnosti vysvětlit změnu NDVI jako odezvu vegetace na probíhající sucho. V rámci výsledků je popsána reakce porostů na epizodu sucha v jarním období roku 2012.

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