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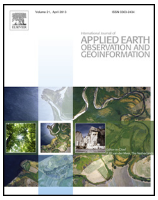

Detection of anomalous crop condition and soil variability mapping using a 26 year Landsat record and the Palmer crop moisture index

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ABSTRACT

Cost-effective and reliable vegetation monitoring methods are needed for applications ranging from traditional agronomic mapping, to verifying the safety of geologic injection activities. A particular challenge is defining baseline crop conditions and subsequent anomalies from long term imagery records (Landsat) in the face of large spatiotemporal variability. We develop a new method for defining baseline crop response (near peak growth) using the normalized difference vegetation index (NDVI) from 26 years (1986–2011) of Landsat data for 400 km^2 surrounding a planned geologic carbon sequestration site near Jacksonville, Illinois. The normal score transform (y_{NDVI}) was applied on a field by field basis to accentuate spatial patterns and level differences due to planting times. We tested crop type and soil moisture (Palmer crop moisture index (CMI)) as predictors of expected crop condition. Spatial patterns in y_{NDVI} were similar between corn and soybeans – the two major crops. Linear regressions between y_{NDVI} and the cumulative CMI (CCMI) exposed complex interactions between crop condition, field location (topography and soils), and annual moisture. Wet toposequence positions (depressions) were negatively correlated to CCMI and dry positions (crests) positively correlated. However, only 21% of the landscape showed a statistically significant ($p < 0.05$) linear relationship. To map anomalous crop conditions, we defined a tolerance interval based on y_{NDVI} statistics. Tested on an independent image (2013), 63 of 1483 possible fields showed unusual crop condition. While the method is not directly suitable for crop health assessment, the spatial patterns in correlation between y_{NDVI} and CCMI have potential applications for pest damage detection and edaphological soil mapping, especially in the developing world.

1. Introduction

We developed a new analysis method to quantify the field-scale spatial variability of crop condition and its temporal response to inter-annual soil moisture variations (Jaynes et al., 2003) for monitoring and mapping applications. The initial motivation for this study was to define a baseline crop condition to enable detection of potential damage from leakage associated with geologic injection activities such as secondary oil recovery ("fracking") and carbon sequestration. For example, concentrated brines (Kaddah and Ghowail, 1964) or carbon dioxide reaching the surface (Male et al., 2010; Noomen and Skidmore, 2008) will most likely be toxic to natural vegetation and crops (Patil et al., 2010) and generate detectable damage. While conceptually straightforward, separating the typical patterns of spatiotemporal variability found in imagery-based crop monitoring (Kawabata et al., 2001; Moran et al., 1997; Peters et al., 2002; Singh, 1989)) from a localized event is a considerable challenge. Flooding, drought, disease, pests, and lodgment, are common and difficult to separate from events arising from injection activities. In addition, crop growth is highly variable, with processes that operate across multiple temporal and spatial scales. At the inter-field scale, differences are introduced by planting time, crop type, and amendment practices. Within-field variability is driven by the interaction between soil properties, landform (Muñoz et al., 2014) (water, chemical, and sediment movement), engineering structures (tile drainage (Naz et al., 2009), grassed waterways, etc.) and the weather conditions for a given year, especially precipitation. Given this complexity, our detection scheme seeks to identify potential anomalous locations that require focused investigations (field work) to determine causation. In addition, the correlation of crop response to variations in weather during the growing season exposes the properties of the underlying soil and can serve as an important source of soil data in remote regions where soil maps and related data (digital elevation models (McBratney et al., 2000; McKenzie and Ryan, 1999)) are scarce or of coarse resolution.

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We define a baseline crop condition from the normalized vegetation index (NDVI) calculated from 26 years of multispectral imagery from Landsat. The possibility of refining baseline estimates through statistical relationships with crop type and inter-annual variations in soil moisture is also investigated. Our primary hypotheses are (a) that field-scale spatial patterns are statistically related to the type of crop and the cumulative soil moisture conditions over the growing season, and (b) that these relationships can be used to refine estimates of expected (field relative) crop condition. We expect such relationships because precipitation, terrain, and soil texture interact to produce spatial variations in water accumulation and retention (Lin, 2003), and these can be used to map crop response patterns (Jaynes et al., 2003; Kaspar et al., 2004), which are accentuated in wet and dry years (Venteris et al., 2004). For example, closed depressions in fields typically have elevated clay and organic matter contents and retain moisture and sediments relative to back slopes and ridges (Ritchie et al., 2007; Schumacher et al., 2005). In dry years this results in enhanced crop growth, but in wet years too much moisture is retained (leading to anoxic conditions, de-nitrification etc. (Zaidi et al., 2004; Zak et al., 1999)), resulting in impeded growth. Mapping these contrasting areas can help in the interpretation of crop condition anomalies and serve as a basis for the delineation of crop response units for precision management applications.

2. Methods

2.1. Study area

Key landscape characteristics surrounding the test site (a 20 km by 20 km area centered on −90.113°W, 39.792°N, northeast of Jacksonville, Illinois) influenced the conduct of our analyses. The climate is continental, with cold winters, hot summers, and an average rainfall of 94 cm (37 inches) per year (Gotsch, 1988). Peak precipitation occurs in summer and is associated with convective (thunderstorm) systems. The spatial variability in precipitation (Huff and Shipp, 1968) within a given year presents a potential challenge for characterizing local soil moisture. The general geomorphic setting of the area is an Illinoisan-age till plain (the depth to bedrock ranges from less than 8 m (25 feet) in incised valleys to 60 m (200 feet) in the uplands (Piskin and Bergstrom, 1994)) overlain by thick (>152 cm (60 inches)) Wisconsinan-age loess deposits (Tama–Ipava–Sable soil association). Land use and land cover (LULC) patterns are strongly related to those of the underlying soils and geomorphology (Fig. S1), with each land use category occupying a dominant soil association. The texture of the upland soils is generally silt loam and silty clay loam, with enhanced clay and organic matter in small closed depressions that are too small (generally less than 100 m in diameter) to be mapped explicitly in the soil survey (Gotsch, 1988). The dominant LULC of this setting is cropping in the form of corn–soybean rotation. The Illinoisan till plain has been exposed to erosion for ∼130,000 years and so the landscape is incised with a well-developed drainage system that flows to the Illinois River (to the west–northwest of the study area). These incised bottom lands generally contain silty alluvial deposits (Rozetta–Hickory–Elco soil association) and the backslope and shoulder soils are typically highly eroded. The dominant LULC in these settings is wooded and pasture lands. Finally, there are several management practices that can affect growth patterns within fields in addition to corn–soybean rotation. Tillage is generally by chisel or moldboard and is conducted in the spring. Rill erosion is controlled by grassed waterways, which often flow into constructed drainage ditches. Brightness patterns in aerial photography reflecting soil moisture content indicate the use of drainage tile for some fields.

2.2. Landsat processing

Defining expected crop condition required long spatio-temporal records. Several years (at least a decade) with contrasting weather conditions were needed, which excluded many high spatial resolution commercial sensors. Sensors were evaluated on the tradeoffs between spatial resolution, temporal resolution, and length of record. MODIS provided images every 1–2 days since 1999 (for Terra) but the 250–1000 m spatial resolution was deemed insufficient. AWiFS (European Space Agency, 2014) had the positive qualities of moderate spatial resolution and a high recurrence rate (∼5 days), but records only extended back to 2003. The best combination of long-term record and spatial resolution was obtained from the Landsat sensors, with records based on the Thematic Mapper instruments extending back to 1986. A challenge was developing a methodology compatible with the low spatial resolution (30 m) and recurrence interval (18 days), which was exacerbated by intermittent cloud cover.

This spatiotemporal analysis of crop condition was based on remote sensing data from the Landsat (NASA, 2014) family of instruments (Thematic Mapper, Enhanced Thematic Mapper+, and Operational Land Imager (for the 2013 test image), collectively abbreviated TM). A cloud-free image closest to the time of peak crop growth was selected for each year (see collection dates in Table S1) over the time span 1986–2011. Each image was radiometrically corrected using the dark-object subtraction technique (Chavez, 1988) and projected to the UTM coordinate system. The normalized difference vegetation index (NDVI) for each grid cell (u) was calculated from

$$\mathrm{NDVI}(\boldsymbol{u}) = \frac{\mathrm{NIR}(\boldsymbol{u}) - \mathrm{RED}(\boldsymbol{u})}{\mathrm{NIR}(\boldsymbol{u}) + \mathrm{RED}(\boldsymbol{u})} \tag{1}$$

where NIR is the near infrared band (TM band number 4) and RED is the red band (TM band number 3). The metric (Fig. 1) provides an estimate of the vigor of plant condition through scaling of the amount of infrared light reflected off the internal portion (mesophyll) of plant leaves.

2.3. Land use and land cover characterization

We categorized the LULC for each of the studied years so that differences between corn and soybeans could be tested. From 1997 to 2011, LULC was obtained directly from the crop data layer (CDL) (Johnson and Mueller, 2010; NASS (National Agricultural Statistics Service), 2013). For earlier dates, we developed classification signatures by correlating the 2010 Landsat data to land cover categories in the corresponding CDL. We used these signatures to identify land cover for the years 1986–1996 via a maximum likelihood classification algorithm. To eliminate the chance that an individual field would contain both corn and soybean (likely due to misclassification), we calculated the majority crop pixel within each field boundary for each year and assigned each field type accordingly.

To test for differences in patterns between soybeans and corn, we digitally delineated fields that were planted in a single crop (soybeans or corn) for each of the studied 26 years. The boundaries do not indicate a constant crop (most of the mapped fields were rotated several times over the span), but rather that the field was planted as a cohesive unit for each individual year. Also, pixels located on the edge of fields often exhibited a mixed response between crops and other land covers. Expected NDVI response was difficult to define for such locations so their inclusion was minimized (Fig. 1). Fields with an area of 2.8 ha (7 acres) or more (approximately 30 Landsat pixels) were included in the analysis, as a minimum estimate of the required number of samples (n) to obtain a meaningful spatial representation.