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Tasseled cap transformation for assessing hurricane landfall impact on a coastal watershed

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A B S T R A C T

Tasseled cap transformation (TCT) has been used to observe relationships among soil moisture, vegetation cover, and canopy condition. Time series Landsat satellite images of high resolution may provide continuous and accurate observations of the land surface, which can be further analyzed using the TCT for natural hazard events. This study explores the use of a unique dispersion phenomenon of TCT for observing the dynamics of vegetation cover and landscape changes due to a major hurricane landfall in the United States. This is based on the Landsat images taken during the Hurricane Bob event, during which the hurricane made landfall in the highly developed New England area in late August 1991. A unique comparison of the TCT time series plots illustrating the relative TCT dispersion phenomenon, which addresses the landfall's profound impact on the Mattapoisett River watershed in 1991, reflects the interactions among biosphere, atmosphere, hydrosphere, and lithosphere in hurricane-prone regions. This analysis can be done without the use of ground truth data and can be further supported by the multitemporal and multidimensional change detection of box plots in terms of brightness and greenness to gain more biophysical interpretation. Findings unveil an inherent earth system process via the varying levels of dispersion among brightness, greenness, and wetness over the coastal watershed with environmental sustainability implications.

1. Introduction

Surface earth processes in different natural hazard events can be analyzed using various types of spatial analysis over a specified time horizon with the aid of geographical information system (GIS) and satellite remote sensing. Hurricanes in America are the same tropical storms known as cyclones in the northern Indian Ocean and Bay of Bengal, and as typhoons in the western Pacific Ocean. In addition to simultaneous monitoring of hurricane impact along the track from meteorological viewpoints, the devastating effect on the land surface after landfall is of importance for understanding and addressing the aftermath. A fast, remote, and comprehensive way for monitoring the surface earth processes associated with each hurricane event is thus deemed critical for earth systems science.

The tasseled cap transformation (TCT) was first developed by Kauth and Thomas in 1976 to describe the growth of wheat cover in an agricultural field. The original work linked the patterns found in Landsat data from the crop lands as a function of the life cycle of the crops. The TCT involves the conversion of original satellite band data into composite band readings, which has arisen out of empirical observations (Watkins, 2005). In other words, it is the weighted sum of separate channel readings over a set of satellite images. This TCT method enhances the spectral information content of Landsat-5 TM data for different implications of the earth's surface. Typically, there are six dimensions in original TCTs. Of them, only three are generally used. They are brightness (measure of soil), greenness (measure of vegetation), and wetness (interrelationship of soil and canopy moisture). This transformation optimizes data viewing that helps in the study of dynamics among soil moisture, vegetation cover, and canopy condition of an area during a natural hazard event.

The assessment of damages to land cover by hurricanes can be done using land cover maps. Land cover maps are an important tool for detecting the influence of human activities and environmental changes (Ran et al., 2009). They are also important in the interpretation of climate change studies as well as understanding the complexities surrounding human activities on a global scale (Jia et al., 2014a,b). Landsat satellite data has proven to be very useful for monitoring land cover change (Townshend et al., 1991). Landsat images were oftentimes used to extract land cover data, such as Normalized Difference Vegetative Index (NDVI) and Normalized Difference Water Index (NDWI), on a global or regional scale (Mcfeeters, 1996; Friedl et al., 2018; Adam et al., 2014).

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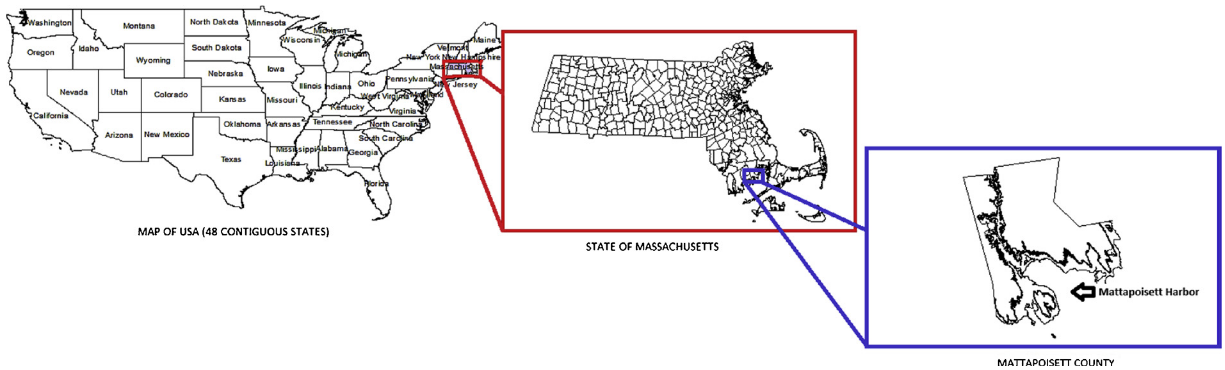

Fig. 1. Geographical location of Mattapoisett River watershed in the hurricane prone region, the United States.

The TCTs can be correlated to NDVI along the greenness dimension since NDVI also deals with the issue of vegetation cover of an area (Rouse et al., 1974) and NDWI area wide. Note that the NDWI is strongly related to plant water and addresses drought or flood conditions using the short-wave infrared and infrared bands of the electromagnetic spectrum (Gao, 1996). On the other hand, it may also be strongly related to open water area which uses the short-wave infrared and green bands of the electromagnetic spectrum (Mcfeeters, 1996). The latter definition was used in this study. The NDVI is a numerical index which uses the visible and infrared bands of the electromagnetic spectrum. In general, healthy vegetation retains a significant portion of visible light and reflects a large amount of near infrared light (Holm et al., 1987). The NDVI is determined using the red and infrared bands. These two bands are sensitive to vegetation cover. The more difference along the lines of these two bands, the denser the vegetation cover will be on the target site. NDVI is used to monitor the live green vegetation of an area of interest and is applicable in a broad range of vegetation studies for the assessment of crop yields (Quarmby et al., 1993; Prasad et al., 2006; Mkhabela et al., 2011), rangelands conveyance capacities (Yengoh et al., 2014), etc. It is often directly identified with other ground parameters such as ground cover percentage (Lukina et al., 1999; Scanlon et al., 2002), photosynthetic movement of the plant (Penuelas et al., 1995; Pettorelli et al., 2005), surface water (Chandrasekar et al., 2010; Fu and Burgher, 2015), leaf territory records which are also known as leaf area index (Carlson and Ripley, 1997; Wang et al., 2005), and the measure of biomass (Anderson et al., 1993). The integration of NDVI/NDWI and TCTs to perform multi-temporal and multidimensional assessment of different hurricane events that made landfall at different types of coastal watershed is still a new topic in the field of earth systems science.

The damage of vegetative cover in Buzzards Bay and Cape Cod in the New England area during the Hurricane Bob event in 1991 was extensive, as assessed by physical inspection (Valiela et al., 1996, 1998). The dispersion phenomenon associated with TCTs before and after this hurricane landfall has not yet been fully understood in the literature. With the availability of synchronous satellite imagery before and after the landfall, it is now possible to examine and explore more inherent surface earth processes with respect to TCTs and NDVI/NDWI simultaneously in a timely manner without having ground truth data (site visits). Comparative statistical assessment, including box plots, dispersion coefficients, and coefficient of variations, may be grouped together to provide a holistic viewpoint with numerical scales to indicate the level of hurricane impact.

As per the above discussion, the enhanced capability afforded by using TCT plots plays an important role in monitoring earth system processes and pinpointing the significant land cover changes that occur before and after a hurricane landfall. Hence, the objectives of this study are to: 1) explore a unique dispersion phenomenon of TCTs driven by hurricane impact based on time series Landsat images when the impact of a hurricane landfall can be observed at the targeted landscape, 2) examine the potential linkage between the three TCT components (greenness, wetness, and brightness) as well as between TCTs and NDVI/NDWI via a cost-effective and holistic approach with the aid of swift observations. We hypothesize that representative indexes such as coefficient of dispersion may be developed to evaluate the brightness, greenness, and wetness reflecting the hurricane landfall impact that can result in higher brightness and wetness as well as lower greenness. We also hypothesize that there are inherent linkages between TCTs and NDVI/NDWI that can provide additional information about the surface earth processes in hurricane landfall events. The science questions to be answered are: 1) can statistical analysis support the inference of varying levels of dispersion in the TCT time series plots and help justify the trend of the brightness, greenness, and wetness for a hurricane landfall event? 2) can a potential linkage between TCTs and NDVI or between TCTs and NDWI echo the trend analyses in terms of the brightness, greenness, and wetness reflecting the hurricane landfall impact?

2. Study area and natural hazard events

The landfall date of Hurricane Bob, one of the most devastating hurricanes in New England's history, was August 20, 1991. The resulting winds and high tidal waves devastated the Buzzards Bay and Cape Cod areas. A high amount of rainfall, almost 20 cm (8 in.), also contributed to the damage (Valiela et al., 1998). Hurricane Bob made landfall in the Mattapoisett River watershed, resulting in a big impact on its landscape. The total cost of the damage caused by the hurricane landfall was $ 1.5 billion 1991 USD, equivalent to $2.64 billion 2017 USD (NCDC, 2017). On-site inspections in the areas of direct impact in Buzzards Bay and Cape Cod have shown the impact of hurricane landfall on vegetative cover resulted in trunk snapping, breakage of limbs, defoliation of trees and death of herbaceous vegetation (Valiela et al., 1998).

The study area is a coastal watershed surrounding the Mattapoisett River and the area is 66.85 square kilometers (Fig. 1). A Digital Elevation Model (DEM) of the watershed is provided to gain a better understanding of the area of interest (Fig. 2). The DEM figure of the Mattapoisett River watershed indicates that the lowest elevation, 6 m, is at the mouth of the river just before it drains out to the bay (Fig. 2a). The elevation increases as we move further inland to the north. The highest elevation is 39 m and is situated at the northwestern side of the watershed. The average elevation is 22.5 m.

The meteorological situation of the Mattapoisett area is characterized by warm summers and relatively mild, wet winters. The summer season lasts from June to September, having an average temperature of 22 °C (71 °F). The winter season, from December to March, has an average temperature below 8 °C (46 °F). There is no significant seasonal variation in the frequency of precipitation in the Mattapoisett harbor area. The annual average rainfall is about 130 cm (51 in.) and is evenly distributed throughout the year (Olimpio and de Lima, 1984).

There are two aspects of geological conditions that are important in