Using Web-enabled Landsat Data time series to analyze the impacts of urban areas on remotely sensed vegetation dynamics

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***Abstract*— Earth is currently experiencing rapid urban growth with >50% of global population living in urban areas. Urbanization occurs as cities expand to meet the demands of increasing populations and socioeconomic growth. Consequently, there is a need for remote sensing research to detect, quantify, and monitor urbanization and subsequent impacts on the environment. Here we used Normalized Difference Vegetation Index (NDVI) data products derived from the Web-enabled Landsat Data (WELD) project to (1) characterize the response of vegetation to urban land cover change and (2) analyze the impacts of urban areas on land surface phenology across rural to urban gradients for two cities located on the United States Great Plains. Here we fit the decade (2003-2012) of NDVI observations as a quadratic function of thermal time to calculate land surface phenology (LSP) metrics and characterize vegetation dynamics on an urban-rural gradient. We found croplands to exhibit greater variation in NDVI at half thermal time to peak compared to forest and developed land cover types. We found a linear relationship between modeled peak height NDVI and NDVI at half thermal time to peak in forest and developed pixels, as well as pixels that experienced a land cover change from cropland to developed. In general, duration of season decreased with distance from the city center in deciduous forest pixels for both cities. Developed pixels had lower modeled peak height NDVI, longer duration of season and greater variation compared to forest pixels.**

I. INTRODUCTION

Urban areas now account for 54% of the global population, [1] projected to increase to 70% by 2050 [2]. Moreover, Earth's global urban population is expected to increase by 2.5 billion during that time period [1]. Urban land cover now covers approximately 0.5% of the planet's land surface, [3] projected to increase by 1.2M km^2 by 2030 [4]. The United States alone has 112,000 km^2 of urban land cover, accounting for 18.5% of global urban areas [5]. Urban population growth and subsequent urban expansion have led to calls for innovative remote sensing research on urban growth detection using finer-resolution data [6] both spatially and temporally [7] as well as additional research on the consequent impacts of urbanization on the biosphere [4,8].

Land surface phenology (LSP) uses remote sensing data to study the timing of biological events in vegetation as influenced by the environment [9]. Studies have used land surface phenology as an indicator of interactions between the atmosphere and the biosphere [10] as a result of changes in climate [11] and land cover/land use [12]. However, past studies have used satellite data with high temporal frequency but low spatial resolution, relative to the scale of city structure, from sensors such as AVHRR or MODIS. Recently, studies have aimed to exploit the newly available Landsat archive to analyze long-term mean and inter-annual variability in phenology [13] as well as continuous land cover change detection [7].

The recently developed Web-enabled Landsat Data (WELD) ten-year time series (2003-2012) offers a novel opportunity to analyze the influence of urbanization and urban areas on land surface phenology at finer spatial and temporal resolution. WELD is a NASA funded project that generates 30 m mosaics over the United States utilizing the Landsat Enhanced Thematic Mapper Plus from 2003-2012. WELD was developed to provide consistent data to be used for remote sensing research of the land surface [14]. Here we used the WELD NDVI product to investigate the impacts of urbanization and urban areas on remotely sensed vegetation dynamics. We focus our analysis on two rapidly urbanizing areas located within the United States Great Plains, a region characterized by isolated, sprawling cities in a temperate agricultural matrix.

II. DATA & METHODOLOGY

A. Study Region

Our study domain contains two cities located in the Great Plains region of the United States. The urban areas selected include Omaha-Council Bluffs, NE-IA and Minneapolis-St. Paul, MN. These cities were selected on the basis that both have seen recent increases in population and urbanized area and are embedded in a temperate, flat, and vegetated landscape. From 2000 to 2011, Omaha, NE (OMA) grew from a population of ~770K to ~875K, a 12.3% increase, while

Minneapolis-St. Paul (MSP) grew from ~2.97M to ~3.32M, a 10.5% increase [15,16]. Between 2001 and 2011, OMA and MSP increased urbanized area by 14.1% and 15.7%, respectively. There is a significant latitudinal separation between these cities: OMA at 41.2° N and MSP at 45.0° N.

B. Datasets

We used the Web-enabled Landsat Data (WELD) NDVI product for the conterminous US (CONUS) and Alaska (http://weld.cr.usgs.gov/). We used impervious surface area (ISA) and land cover type (LCT) data from the 2001, 2006, and 2011 versions of the National Land Cover Database (NLCD) [17,18]. The data are at a spatial resolution of 30 m and are available for download from the Multi-Resolution Land Characteristics Consortium (MRLC) website: (http://www.mrlc.gov) [17]. Temperature data were obtained from the MODIS Aqua Level 3 Land Surface Temperature 1 km 8-day composites (day/night) from the LPDAAC (http://lpdaac.usgs.gov/) for 2003-2012.

C. Methods

We quantified urbanized area and change in each city using the 2001-2006-2011 NLCD ISA dataset. We then used the LCT dataset to classify our study pixels. We used the WELD platform to order weekly time series for all of the selected 30 m pixels. To characterize the impacts of urban land cover change on vegetation dynamics, we used the LCT change information to select 25 pixels where LCT was converted from "croplands" to "developed" LCT in the OMA study region. We ordered 25 pixels classified as "croplands" for comparison with the change pixels.

To analyze the impacts of urban areas on LSP metrics on a rural-urban gradient, we ordered 100 pixels classified as "deciduous forest" spanning a 225 km east-west transect across MSP and 25 pixels spanning a 110 km transect across OMA. We investigated the impact of urban areas on duration of season and modeled peak height in NDVI as a function of distance from city center. We define city center as the central business district (CBD); in MSP the city center includes both the Minneapolis and St. Paul CBDs. We calculated Euclidean distance from city center for each site, using the minimum distance of the two centers for MSP pixels. We ordered an additional 100 pixels in the MSP region classified as "developed open space", "developed light intensity", or "developed medium intensity", herein referred to as developed. Fig. 1 shows the distribution of forest and developed pixels across the MSP study region.

We excluded NDVI observations using the ACCA and DT cloud state metrics and saturation flag from WELD [14]. We excluded poor quality or non-vegetated NDVI observations using two baseline thresholds: NDVI < 0.1 for forest and developed pixels, and NDVI < 0.2 for cropland pixels.

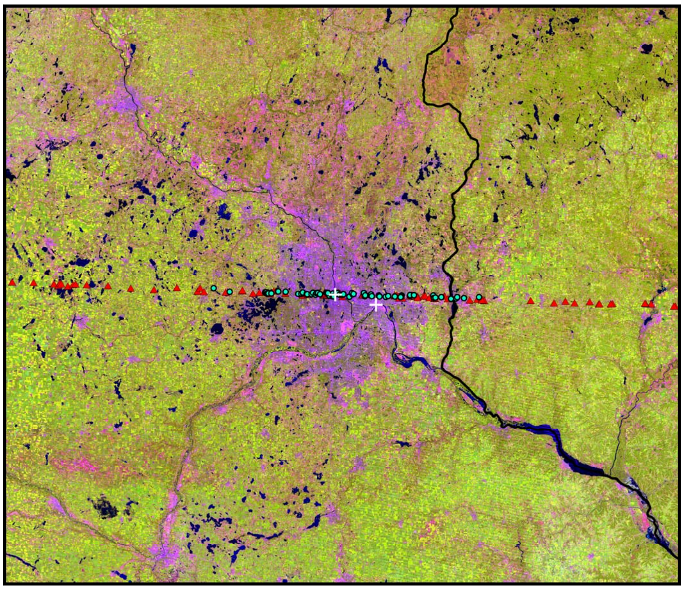

Fig. 1. 2012 Annual WELD false color composite (R = band 5; G = band 4; B = band 3) of MSP with forest sites as red triangles and developed sites as cyan circles. City center for Minneapolis and St. Paul are white crosses.

We used the 8-day land surface temperature composites (day/night) as a vector for min/max temperatures to calculate Accumulated growing degree-days (AGDD), a measure of thermal time, for each city from 2003-2012. We then fit the NDVI time series as a quadratic function of AGDD, using the decade of observations. We focused on the following LSP metrics: modeled peak height NDVI (PH), thermal time to modeled peak height (TTP), NDVI at half thermal time to peak (NDVI at half-TTP), duration of season (DOS) and coefficient of determination. Pixels with a coefficient of determination < 0.5 were excluded from further analysis. Fig. 2 illustrates the use of fitting the convex quadratic model to the decade of NDVI vs. AGDD observations and the associated phenometrics calculated from the model.

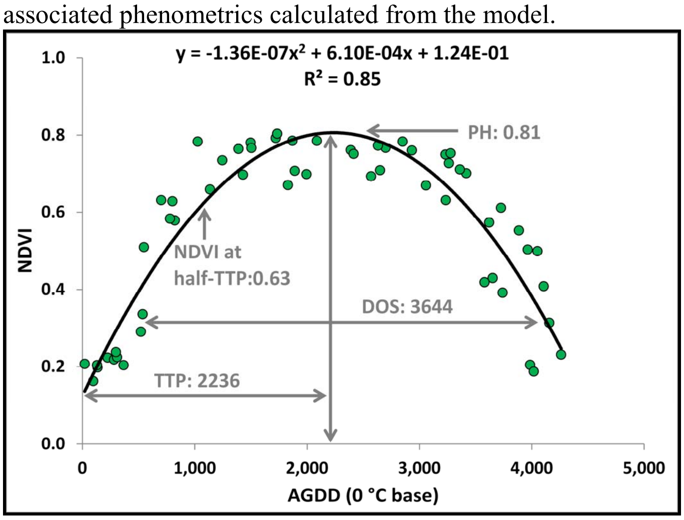

Fig. 2. WELD 2003-2012 NDVI vs. Accumulated Growing Degree-Days for a forest pixel located in the Minneapolis-St. Paul study region showing the land surface phenology metrics used for analysis.

III. RESULTS

A. LSP Characteristics and Response to Land Cover Change

Fig. 3 includes the modeled PH vs. NDVI at half-TTP for all OMA sites. We found a distinct difference in the relationship between annual vegetation (croplands) and perennial vegetation (developed and forest) (Fig. 3). A linear relationship was observed between PH and NDVI at half-TTP for developed and forest pixels. No significant relationship was found in the cropland pixels (Fig. 3). The cropland-to-developed change pixels exhibit similar dynamics to cropland pixels before the land cover change occurred. After the land cover change occurred, the pixels exhibit a linear relationship similar to developed and forest pixels. Both PH and NDVI at half-TTP are lower in post-change pixels compared to developed and forest pixels. Fig. 4 shows the modeled PH against NDVI at half-TTP illustrating the linear relationship between PH and NDVI at half-TTP for developed and forest pixels in MSP.

B. Duration of Season

Fig. 5 shows the results for modeled duration of season vs. distance from city center. The latitudinal difference between OMA and MSP is evident, with longer growing seasons for OMA forest pixels located outside of the city center. In general, duration of season increases with proximity to city center in both cities for forest pixels. However, the relationship is non-linear. Also, we found modeled PH to decrease with proximity to city center in forest pixels.

C. Forest vs. Developed Sites

Fig. 6 includes the duration of season vs. distance from city center for developed and forest pixels in the MSP study region. Duration of season was longer in developed pixels compared to forest pixels. Greater variation in duration of season was found in developed pixels compared to forest pixels. This variation could be attributed to the heterogeneous nature of developed areas, often including rooftops, roads, suburban lawns and tree canopies in a single pixel.

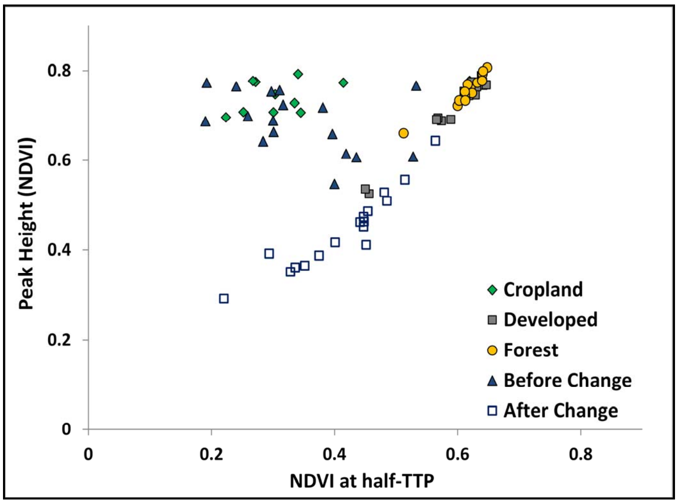

Fig. 3. PH vs. NDVI at half-TTP by LCT for OMA pixels. In blue are the cropland-to-developed change pixels indicating the modeled NDVI metrics before (triangles) and after (open squares) the land cover change occurred.

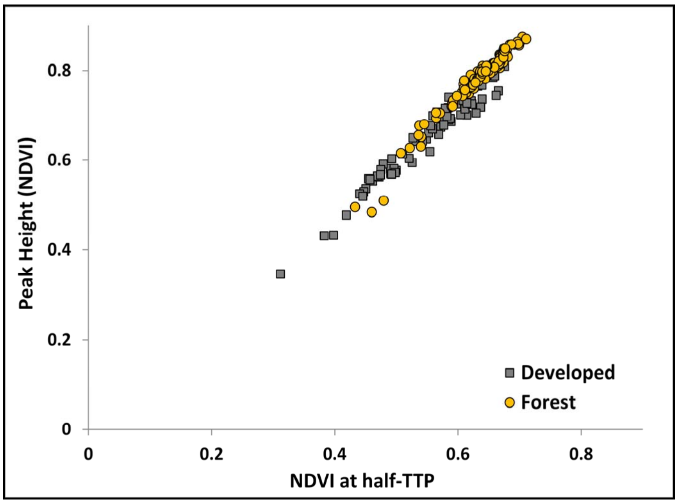

Fig. 4. PH vs. NDVI at half-TTP by land cover type for MSP study pixels.

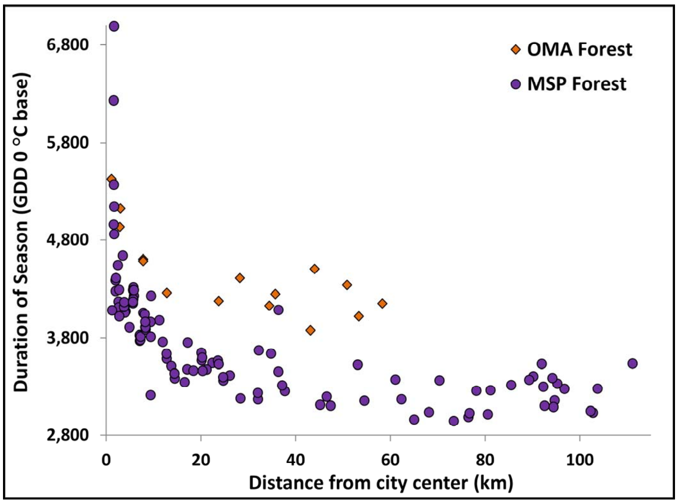

Fig. 5. Duration of season vs. distance from city center for forest pixels from both cities showing longer duration of season with proximity to city center and latitudinal differences in season length.

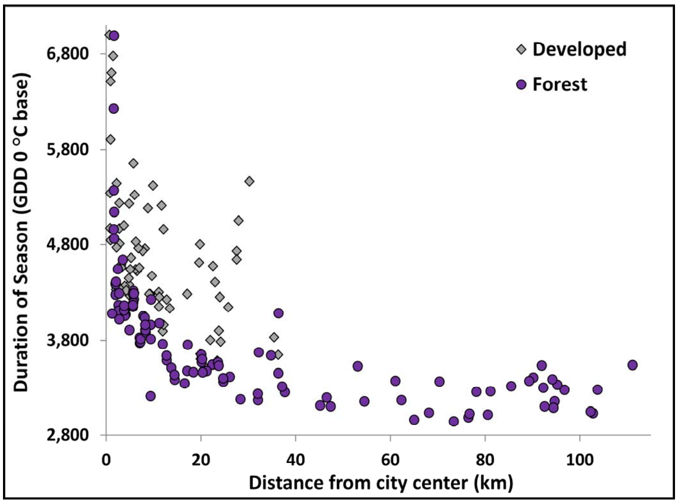

Fig. 6. Duration of season vs. distance from city center for MSP forest and developed pixels.

IV. Conclusions

NDVI at half-TTP is a measure of the rate of green up of vegetation and is linked to the start and duration of the growing season for vegetation. Modeled NDVI at half-TTP exhibits a positive linear relationship with modeled PH for perennial vegetation. This linear relationship suggests that the annual development of perennial vegetation is driven by atmospheric conditions such as thermal time. Greater variation in NDVI at half-TTP for cropland pixels suggests that croplands may not be suitable for analyzing the impacts that urban areas exert on the surrounding environment, because annual cropland LSP dynamics are driven by management factors, such as choices of crop varieties, irrigation, and the timing of tillage. The finding that duration of season increases while peak height NDVI decreases with proximity to city center suggests that, although urban vegetation may benefit from longer growing seasons, urban vegetation may be less productive than suburban and rural vegetation. An earlier version of our study used first order weather station data to calculate AGDD, with similar results. However, we found that using spatially-explicit temperature data from the MODIS LST product provided better insight into the varying local atmospheric conditions that influence growing season length.

Characterization of urban LSP has been relatively understudied in the past due to spatial and temporal resolution constraints. The recently developed CONUS WELD 10-year time series offers a novel opportunity to monitor land surface phenology at a relatively high spatial resolution of 30 meters. The availability of medium resolution remote sensing time series provides a unique opportunity to study land surface phenology in complex, heterogeneous, and dynamic urban environments and understand the impacts of urbanization and urban areas on the environment both within and nearby urban areas. Maps of urban LSP can be useful as model inputs to investigate surface-atmosphere processes [19]. While 30 m resolution data lacks the resolution necessary for specific urban vegetation mapping [19], a recent study found significant agreement between NDVI and biomass in the city of Syracuse, NY [20]. Even more recently, Global WELD was developed to provide monthly Landsat data time series for the planetary land surface, excluding Antarctica. The Global WELD product is yet another data resource to study LSP dynamics at finer spatial resolution. In conclusion, this study has explored the potential of using the CONUS WELD data product as a source from which we can characterize urban land surface phenology along a rural-suburban-urban gradient at medium spatial and temporal resolution.

Acknowledgment

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