Satellite-based assessment of rapid mega-urban development on agricultural land

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Abstract

Observations of urbanization will provide a framework for understanding the biophysical processes caused by artificial land changes. Sejong Multifunctional Administrative City (MAC) is under development since 2006 to decentralize the function of Seoul, the capital city of South Korea. MAC was originally agricultural land and now is rapidly developing to mega-city. Using U.S. Air Force Defense Meteorological Satellite Program’s Operational Linescan System (DMSP-OLS) and Moderate-resolution Imaging Spectroradiometer (MODIS) satellite data, the spatio-temporal characteristics of nighttime light (NTL) emission, normalized difference vegetation index (NDVI), land surface temperature (LST), and surface albedo were investigated in MAC and its adjacent cities. NTL was generally stronger in the presence of vegetation degradation and surface warming conditions. LST was negatively correlated with a growth in vegetation. Those relationships among NTL, LST, and NDVI were shown both in temporal change at MAC and spatial variation of MAC’s adjacent cites. Further, because the ratio value of LST to NDVI was similar in temporal and spatial scales, these two indices can be used as important indicator of urbanization. However, surface albedo is not suitable to represent the temporal transition from rural to urban state because tall buildings can often bring relatively low surface albedo by blocking outgoing radiation.

Key words: Albedo, Land surface temperature, Nighttime light, Urbanization, Vegetation index

1. Introduction

The development from rural state into urban state generally creates substantial modifications of land surface, landscape patterns, and even local climate through dramatic changes of land use (Feddema et al., 2005; Deng et al., 2009). Thus, observations of urbanization can provide a framework for assessing the complex biophysical processes caused by artificial land use changes (Alberti, 2005). However, it is difficult to assess urbanization by using quantitative evaluation because the meaning and indicator of urbanization is not clearly defined (Carlson and Arthur, 2000; Taubenböck et al., 2009). Satellite remote sensing measurement can provide the temporal data of biophysical conditions changed by urbanization over a broad area (Weng, 2002). Photographic imageries from remote sensing methods are often used to realize the reduction of rural area and expansion of urban area. However, the analysis of photographic RGB colors has limitations to numerically evaluate environment-
et al. (2015) have compared LST with NTL based on positive linear correlation and LST with NDVI based on negative linear correlation related to urban heat islands. Hou et al. (2014) have reported an increase in $\alpha$ according to vegetation degradation and surface sealing through urbanization. Akbari et al. (2009) have demonstrated that lower absorbed energy caused by increased $\alpha$ results in surface cooling. On the other hand, Yang and Li (2015) have shown that taller and denser buildings cause decreases in $\alpha$.

Sejong Metropolitan Autonomous City is now rapidly changing from rural to mega-urban area through the development plan of the Korean government. This unusual city should be useful to understand the change from rural state into urban state. It was selected as our study area to analyze temporal changes in NTL, NDVI, LST, and $\alpha$ according to the progress of rural urbanization. The objective of this study was to evaluate the progress of rural urbanization using the inter-comparisons of NTL, NDVI, LST, and $\alpha$. The values of these four variables were compared to those measured in Sejong Metropolitan Autonomous City and its adjacent cities.

2. Data and methodology

The construction plan of Sejong Metropolitan Autonomous City, also known as Multifunctional Administrative City (MAC), was drawn in 2006 to decentralize the function of Seoul, the capital city of South Korea. The policy of building management near the construction site for MAC was formulated in 2007. MAC construction began in 2009. 36 government ministries and agencies had completely moved to MAC on July 2012. In Fig. 1, the photographic imagery of MAC in 2007 mostly shows agricultural and mountainous areas, but large areas changed to buildings and roads in 2014. As this process is a very rare case of fast land use change from rural to mega-urban area, we investigated the temporal changes in NDVI, LST, and $\alpha$ of Sejong MAC and compared them to those measured in 11 adjacent cities. Instead of compiling data according to the administrative district of each city, we determined the study area in an appropriate size of rectangle for each city to analyze the characteristics of urbanization, rather than the expansion of urban area (Fig. 2). The size and position of each rectangle for the 11 adjacent cities were determined as the higher values of NTL ($> 45$ DN) and LST ($> 302$ K) than the other pixels in study area.

The NTL satellite imagery was obtained from the U.S. Air Force Defense Meteorological Satellite Program’s Operational Linescan System (DMSP-OSL). To detect persistent artificial lighting, after discarding ephemeral lighting such as wildfire, stable light average product annually scaled at a resolution of about 1 km was used in the DMSP-OSL data. The range of the image’s digital number (DN) was 1–63, with the lowest value representing the darkest condition at nighttime. In our study, we used DMSP satellite F15 for 2001–2006, F16 for 2007–2009, and F18 for 2010–2013. To directly compare the DN values of NTL produced by different satellites, annual values was corrected by using a second-order regression model presented by Elvidge et al. (2014).
The average values of NDVI, LST, and \( \alpha \) in August during 2002–2014 are used because August has the highest vegetation greenness of the summer months except during the monsoon rainy period. 1 km resolution would be suitable for representing the spatio-temporal changes of each city in our study area. Thus, the 16-day scaled NDVI (0.0–1.0) with 1 km resolution from Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 5 (MOD13A2.005) was used. MODIS LST was obtained from MOD11A2.005 of an 8-day product scaled at 1 km resolution. \( \alpha \) for the shortwave radiation was calculated by using MODIS Bidirectional Reflectance Distribution Function (BRDF) product MCD43B1 with local noon and the optical depth of 0.2.

The progress of rural urbanization is difficult to numerically represent. However, urban and rural areas can be distinguished by obviously different landscapes. Thus, the relative difference of surface indicators between urban and rural areas is useful to understand the phenomena of urban areas (Cho et al., 2016). In this study, to represent relative changes of NDVI, LST, and \( \alpha \) in MAC and its 11 adjacent cities, we selected a native forest area in Geryongsan National Park as rural reference area because it has a well-vegetated and stable landscape with weak human activities. The relative NDVI \( (r_{NDVI}) \) and relative \( \alpha (r_{\alpha}) \) are the ratios of the target pixel values against the reference pixel value. Relative LST \( (r_{LST}) \) is the difference between target pixel value and the reference pixel value.

\[
\begin{align*}
    r_{NDVI} &= \frac{NDVI_{t}}{NDVI_{ref}} \\
    r_{LST} &= LST_{t} - LST_{ref} \\
    r_{\alpha} &= \frac{\alpha_{t}}{\alpha_{ref}}
\end{align*}
\]

where the subscripts \( t \) was a given target pixel, and \( ref \) was the rural reference pixel.

### 3. Results and discussion

Figure 3 shows the changes in NDVI and NTL at MAC. From 2006 to 2007, both values began to decrease, which coincided with the decision of the construction plan. From 2007 to 2008, both NDVI and NTL values were decreased abruptly because the remained wild vegetation and agricultural fields were rapidly reduced while the existing buildings were partly removed to prepare for the construction of MAC. From that time onward, the NDVI value was decreased continuously until 2013 even though government ministries and agencies were completely moved to MAC in 2012. However, the darkened NTL emissions during 2006–2009 were increased gradually with the progress of building construction. In contrast to MAC, NTL and NDVI in 11 adjacent cities did not have significant temporal variations (data not shown).

Figure 4 represents the change in surface thermal condition (by using \( r_{LST} \)) and reflectance (by using \( r_{\alpha} \)) according to vegetation degradation (by using \( r_{NDVI} \)). The 14-year averages of \( r_{LST} \) and \( r_{NDVI} \) of 11 adjacent cities had linear negative relationships with high correlation coefficient \( (r) \) values (Fig. 4a). The DN of NTL was mostly higher with the decreases in \( r_{NDVI} \) and the increases in \( r_{LST} \). The decreased \( r_{NDVI} \) (degraded vegetation) was typically possible, resulting in increases of \( r_{LST} \) (increased urban heating). Thus, the relationship between \( r_{NDVI} \) and \( r_{LST} \) can be useful criterion for indicating the degree of environmental effect by rural urbanization.

The annual changes of \( r_{LST} \) with regard to \( r_{NDVI} \) at MAC \( (slope = -8.25 \) in Fig. 4b) were similar to the 14-year averaged ratio of the \( r_{LST} \) against \( r_{NDVI} \) in the 11 cities \( (slope = -8.71 \) in Fig. 4a). However, the \( r_{LST} \) values (intercept) of each year against the \( r_{NDVI} \) at MAC were lower than the average values of other cities. In terms of the intercept of regression line, the \( r_{LST} \) against \( r_{NDVI} \) of MAC \( (9.318) \) was lower than that of other cities \( (12.63) \). This might have occurred because even though the vegetation at MAC had been degrading due to intensive land use caused by city developing processes, the city area for the MAC facility was not fully established yet. Thus, if the function of urban facilities in MAC had been completed as the plan, the \( r_{LST} \) and \( r_{NDVI} \) in MAC would have been located near the regression line of Fig. 4a.

In Fig. 4c, the \( r_{\alpha} \) values of all plots were higher than 1.0 because the surface reflectance was generally higher than that of rural areas with higher vegetation biomass. It is because the surface \( \alpha \) in urban area could be higher than rural area due to the high-albedo urban materials (e.g., Taha, 1997). However, Fig. 4c showed that a positive linear correlation appeared between the 14-year averages of \( r_{\alpha} \) and the \( r_{NDVI} \) of 11 adjacent cities. In addition, the most developed city among 11 cities had an \( \alpha \) value close to that of the reference rural area. Yang and Li (2015) reported that the increasing height of buildings can be attributed to reduced \( \alpha \) because the outgoing radiation from the surface can be partially blocked by tall buildings. Indeed, the surface \( \alpha \) is determined not only by surface materials but also by its structure (e.g., Brest, 1987). Therefore, given that the close association between the existence of tall buildings and intensified urbanization, the \( \alpha \) will be useful to indicate the degree of urbanization.

The annual changes of \( r_{\alpha} \) with regard to \( r_{NDVI} \) at MAC was not similar to the 14-year averaged ratio of the \( r_{\alpha} \) against \( r_{NDVI} \) in the 11 cities (Fig. 4d). Indeed, there was no significant
temporal relationship between $r_\alpha$ and rNDVI at MAC. During 2007–2009, $r_\alpha$ at MAC was remarkably increased. This result is consistent with the early development phase with a sharp decrease in vegetation (see Fig. 3). The change in landscape by surface sealing such as the expansion of roads and increases in the number of concrete facilities might have caused this increase in surface reflectance. Through the variations of $r_\alpha$ during 2006–2013, the value of $r_\alpha$ in 2014 reached similar value measured in 2006, the year MAC construction was planned. Thus, while the spatial relationship between $r_\alpha$ and rNDVI could be useful to evaluate urbanization among developed cities, the temporal variable of surface albedo is not suitable to comprehend the stage of the transition from rural to urban.

4. Conclusions

In this study, to investigate the changes in land surface conditions caused by progress of rural urbanization, we conducted spatio-temporal analysis of NTL, NDVI, LST, and $r_\alpha$ in a rapidly developing city and its adjacent cities. Our data showed that NTL was generally stronger under conditions of decreased vegetation and increased surface warming. Thus, satellite-derived NTL data can be a useful indicator for spatial evaluation to show characteristics of vegetation degradation and microclimate changes caused by urbanization. In addition, we found that the temporal change of LST to NDVI as the rural urbanization at MAC was similar to spatial relationship between LST and NDVI for the adjacent cities. This will be important criterion to define the degree of rural urbanization.

The differences of $r_\alpha$ values among cities can indicate the degree of urbanization in terms of vegetation degradation as indicate by NDVI, but not in terms of urban facilities as indicated by NTL. However, the progress of transition from rural to urban at a certain place is not well represented by $r_\alpha$. On the other hand, a spatio-temporal linear relationship between urbanization and surface warming in urban areas was found. This can be useful for evaluating the spatial distribution of urbanization intensity and temporal progress of urbanization. However, the sensitivity between land degradation and warming can change according to the type of facilities in a city owing to the selection of construction materials, heating management of the building, and other factors (Taha, 1997). Thus, further investigation on the relationship between LST and NDVI in various urban areas is required.

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