Landscape Ecol Eng (2005) 1: 169–176
DOI 10.1007/s11355-005-0021-1

ORIGINAL PAPER

Dong-hoon Shin · Kyoo-seock Lee

Use of remote sensing and geographical information systems to estimate green space surface-temperature change as a result of urban expansion

Received: 24 May 2005 / Revised: 30 June 2005 / Accepted: 21 July 2005 / Published online: 15 November 2005

Abstract A combined approach of remote sensing (RS) and geographical information systems (GIS) was used in this study to identify the impact on urban surface radiant temperature (SRT) of urban green-space change. Urban SRT increases as green-space area is converted into non-green-space area. Also, well preserved green space and newly connected green space contribute to a decrease of the SRT. Seoul Metropolitan area is rapidly expanding. Existing urban SRT studies have, however, mainly been conducted for Seoul City. The most rapidly expanding area in Korea is now the Seoul suburban area, for example the Mt Gwanggyo area. Although changes of SRT and normalized difference vegetation index (NDVI) as a result of land-use change have been measured in many other studies, the results in these studies were derived from data from different seasons. Also, these studies did not examine a newly expanding area. Considering these problems, the same seasonal multitemporal data were used in this study to derive the SRT change for the same season in different years. This study confirmed the importance of effective management and location of urban green space for urban SRT mitigation. Ultimately, the impact on urban SRT of urban green-space change should be regarded as an important factor in urban planning.

Keywords Surface radiant temperature (SRT) · Land-use change · Green space · Urban expansion

Introduction

Green space provides a natural environment for urban residents (Taylor et al. 1995) and contributes to stabilization of the urban climate (DTLR 2002; DCAUL 2003). It also increases the biodiversity of urban areas, enhances noise absorption, reduces air pollution, provides sustainable urban drainage, and reduces urban air and surface temperature (Miller 1997). The urban temperature mitigation effect of green space helps make cities more comfortable places. Daytime air temperatures have been found to be approximately two to three degrees lower in urban green space than in the surrounding area (DTLR 2002). Green spaces intercept solar energy directly by providing shade and indirectly by covering surfaces that reflect or re-radiate solar energy. Thus, the cooling effects of urban green space have an important role in reducing urban environmental problems; it is therefore necessary to plan green space carefully. Unfortunately, these green spaces shrink during urban expansion, which has occurred rapidly in Korea since the 1960s. As a result, green-space areas have decreased and the existing green spaces have deteriorated. Because urban structure materials such as asphalt and concrete store heat in the daytime and cool slowly after sunset, they have become the main factor in the increase in the urban surface radiant temperature (SRT). Urban SRT increase is primarily because of the smaller amount of green space in central cities than in suburbs and rural areas. The SRT is monitored by analyzing data from a remote-sensing (RS) satellite to determine the effect on thermal difference of land cover and use. Satellite RS thermal infrared (TIR) data can capture the holistic view of urban SRT.

Many studies have used TIR data from airborne (Voogt and Oke 1997; Lagouarde et al. 2004), advanced very-high-resolution radiometer (AVHRR) (Gallo and Owen 2002), and Landsat Thematic Mappers (TM)/enhanced Thematic Mapper plus (ETM+) (Munier and Burger 2001; Qin et al. 2001; Yang and Wang 2002; Weng 2003) to confirm the relationship between the spatial structure of urban surface-temperature (ST) patterns and land-cover types. The relationship between ST and normalized difference vegetation index (NDVI) has been studied. These studies used data from AVHRR

D. Shin (✉) · K. Lee
Department of Landscape Architecture,
Sungkyunkwan University,
300 Chunchun-dong, Changahn-gu,
440-746 Suwon, Gyeonggi-do, Korea
E-mail: wonder-boy@hanmail.net
E-mail: leeks@skku.edu

(Roy 1997; Kant and Badarinath 2000), Landsat TM/ETM+ (Jo et al. 2001a; Weng et al. 2004; Southworth 2004), and an advanced thermal and land applications sensor (ATLAS) (Lo et al. 1997). Although many studies using AVHRR TIR data have been conducted to confirm SRT on a global scale (Goetz 1997; Roy 1997; Kant and Badarinath 2000; Gallo and Owen 2002), such data are of limited value for detecting SRT changes as a result of land use in complicated sites, for example that studied in this work, because the spatial resolution is coarser (1.1 km) than that of the Landsat TIR (120 m). Because land use in the study site was complex and rapidly changing, Landsat TM images were used to detect SRT changes, because they have finer spatial resolution. This study investigated the change of urban green space SRT during urban expansion by using RS and geographical information systems (GIS). RS and GIS have been widely used to detect land-use change and identify SRT change (Weng 2001). Although the areas south of Seoul are undergoing rapid urban expansion, most studies have focused on Seoul City (Jo et al. 2001a; Park 2001; Cho and Shin 2002).

The most rapidly expanding areas in Korea are now suburban areas, for example the Mt Gwanggyo area. Changes of SRT and NDVI as a result of land-use change have been confirmed in other studies (Jo et al. 2001a; Park 2001; Cho and Shin 2002). These studies used data from different seasons, however, and have not investigated the newly expanding areas. Because of these problems, this study used multitemporal data from the same seasons to derive the SRT change for the same season in different years.

This study investigated the new residential development site in Seoul and the newly expanding Mt Gwanggyo urban area. The objective of the study was, therefore, to estimate the urban green-space SRT change during urban expansion by using RS and GIS and to provide data and information for urban green-space planning.

Materials and methods

Study site

The study sites were the Mt Daemo and Mt Gwanggyo areas located south of the Han River in South Korea. Geological features of the former study site include Precambrian Era gneisses as part of Gyeonggi Gneiss Complex and various igneous rocks of the Mesozoic Era. Also, quaternary alluvium is deposited along Tahn Stream and Yangjae Stream (Korea Institute of Geoscience and Mineral Resources 1972, 1975, 1982) in the Mt Daemo area.

The Mt Gwanggyo area has been urbanized rapidly, mainly because of new satellite town developments such as Suji at Yongin City, Bundang, Suwon, Anyang City, and Uiwang City. Also, forests have been fragmented by road construction, for example the Seoul beltline highway, the Shingal–Ansan highway, and the Gwacheon–Uiwang expressway. Former green spaces, for example cropland and forests, have been converted into urban area. After urbanization the original landscape changed rapidly. Urban forests have shrunk and become fragmented by road and residential housing construction.

The Mt Daemo area is in Gangnam-gu, Seocho-gu, and includes Mt Guryong, Yangjae Stream, and Tahn Stream south of the Han River in Seoul. Since the 1970s the population of Seoul has grown rapidly, mainly because of urbanization, and development has begun for housing construction. The Mt Daemo area was incorporated into Seoul by the Seoul Administrative District Expansion Plan in 1963 (Sohn 1998). Mt Daemo surrounds the Suseo district developed from 1989 to 1993. Agricultural areas dedicated as greenbelt are located south of Mt Daemo and Mt Guryong. Figure 1 shows the study site.

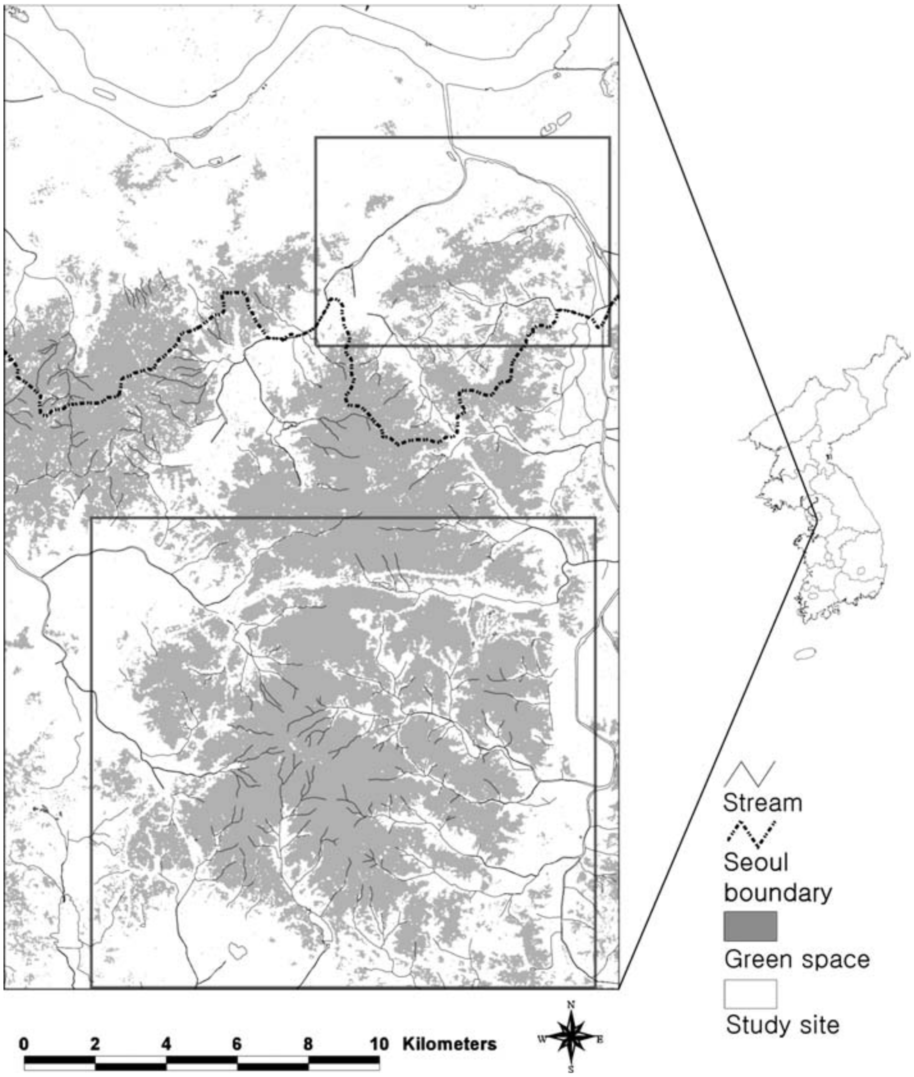
Data

Landsat TM images taken on May 20 1987 and May 21 1999 were used to derive SRT using RS data (Table 1). Initially, May 2003 ETM+ data were used. Just before this date when the TM images were taken, however, tens of millimeters of precipitation were recorded at the study area, so the 1999 TM image was used in this study. To verify the effects of rainfall on SRT, 5-day rainfall information for both sets of data were checked, including the day the Landsat TM scene was taken, the previous two days, and the next two - days (May 18 1987 to May 22, 1987 and May 19 1999 to May 23 1999) in Seoul and Suwon provided by Korea Meteorological Administration (KMA). Ground measured automatic weather station (AWS) temperature data in Seoul and Gyeonggi-do were also used at 34 points to verify satellite-derived SRT. A 1:3,000 scale Seoul Metropolitan Biotop Map and an IKONOS satellite image were used to verify land-use classification and urban green space location. Tables 1 and 2 show RS data and other data including the GIS data used in this study.

Methods

Thematic Mapper images taken on May 20 1987 and May 21 1999 were geometrically corrected to 30.0-m resolution by using the first-order polynomial transformation and nearest-neighbor resampling. For reference data, 1:25,000 and 1:5,000-scale digital topographic maps were used to select ground control points (GCPs). Root mean square (RMS) errors of 1987 and 1999 images were recorded as 0.295 and 0.30 pixels, respectively. Land cover was then classified using the hybrid classification method for both TM data. The Seoul Metropolitan Biotop Map was used to confirm the land use classification in 1999. It was reclassified into five

Fig. 1 The study site



classes—urban, agricultural area, forest, bare soil, and water.

For spatial analysis between land-cover classification, SRT, and NDVI, TIR data were resampled with the same spatial resolution as the other bands of the TM image. So, each TIR pixel was subdivided into 30 m×30 m spatial resolution pixels to compare the data spatially. The RS and GIS software PCI ver. 7.0 (RS) and ArcView ver. 3.2 (GIS) were used in this study.

Surface radiant temperature was derived from TM TIR data. To derive the corresponding spectral radiance value from the digital number (DN) of the TM TIR data, the following equation (Eq. 1) was used (Landsat Project Science Office 2002).

$$L_\lambda = \left(\frac{\mathrm{LMAX}_\lambda - \mathrm{LMIN}_\lambda}{Q_{\mathrm{calmax}}}\right) \times Q_{\mathrm{cal}} + \mathrm{LMIN}_\lambda \qquad (1)$$

where L_λ is the spectral radiance at the sensor's aperture in W/(m^2 sr μm), Q_{cal} is the quantized calibrated pixel value in DN, Q_{calmin} is the minimum quantized calibrated pixel value (DN = 0) corresponding to $LMIN_\lambda$, Q_{calmax} is the maximum quantized calibrated pixel value (DN = 255) corresponding to $LMAX_\lambda$, $LMIN_\lambda$ is the spectral radiance scaled to Q_{calmin} in W/(m^2 sr μm), and $LMAX_\lambda$ is the spectral radiance scaled to Q_{calmax} in W/(m^2 sr μm). For TM, $LMIN_\lambda$ is 1.2378 and $LMAX_\lambda$ is 15.303 (Chander and Markham 2003).

Table 1 RS data used in this study

Data source	Resolution	Date	Data type
Landsat 5 TM	Visible: 30 m TIR: 120 m	May 20 1987 May 21 1999	Digital
IKONOS satellite image	1 m	May 2002	Digital (pan-sharpened)

Table 2 Reference data used in this study

Data source	Scale	Date	Data type	Publisher
Topographic map	1:25,000 1:5,000	1996	Digital	National Geographic Information Institute
Seoul Metropolitan Biotop Map	1:3,000	2000	Digital	Seoul Development Institute
AWS temperature data	–	May 18 1987 to May 22 1987 May 19 1999 to May 23 1999	–	Korea Meteorological Administration

The spectral radiance was then converted into the absolute temperature. This is the effective at-satellite temperature of the viewed earth–atmosphere system under the assumption of unit emissivity and using pre-launch calculation. The following conversion formula (Eq. 2) was used (Landsat Project Science Office 2002).

$$T_\mathrm{b} = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \quad (2)$$

where T_b is the effective at-satellite bright temperature in Kelvin, K_2 is the pre-launch calibration constant 2 in Kelvin, K_1 is the pre-launch calibration constant 1 in W/(m^2 sr μm), and L_λ is the spectral radiance at the sensor's aperture. For Landsat TM, the constants K_1 and K_2 are 607.76 and 1,260.56, respectively (Chander and Markham 2003).

The temperatures obtained above are, however, referenced to a black body, so emissivity was corrected according to the nature of land cover. The emissivity corrected SRT were computed as follows (Eq. 3) (Weng 2001; Weng et al. 2004):

$$S_t = \frac{T_\mathrm{b}}{1 + (\lambda \times T_\mathrm{b}/\rho) \times \ln \varepsilon} \quad (3)$$

where S_t is the emissivity-corrected SRT, λ the wavelength of emitted radiance, ρ is $h{\times}c/\sigma$ (where σ is the Boltzmann constant, h is Plank's constant, and c the velocity of light),T_b the at-satellite bright temperature, and ε is the emissivity. Emissivity correction was done for each land cover class—urban, forest, agriculture, bare soil, and water (Lillesand and Kiefer 1999). Finally, the absolute temperature was converted into degrees Celsius. Then, SRT was verified by referring to Seoul (23 points) and Gyeonggi-do (11 points) AWS temperature data for May 21 1999. In this study the relationship between SRT and NDVI was also investigated. The NDVI was used in SRT estimation because the amount of vegetation present is an important factor and NDVI can be used to infer the general condition of vegetation (Weng et al. 2004).

Results and discussion

Table 3 shows land-cover change and the corresponding mean SRT change at the study sites from 1987 to 1999. In the Mt Daemo area the overall green-space area (forest, agriculture, and water) decreased by 7.41 km^2 and non-green-space area increased by the same amount, as shown in Table 3. As non-green-space area, urban area increased by 8.12 km^2 because agricultural area and bare soil were changed into urban area during urban expansion developments such as the Suseo district development. Bare soil decreased by 3.84 km^2 for construction. As green-space area, forest and agricultural areas decreased by 0.56 and 7.10 km^2, respectively. Water area increased by 0.25 km^2. Agricultural area was changed into forest by 1.12 km^2 at the Yangjae Urban Forest. In the Mt Gwanggyo area the overall green-space area (forest, agriculture, and water) decreased by 32.16 km^2 and non-green-space area increased by the same amount (Table 3). As non-green-space area, urban area increased by 34.51 km^2 during urban expansion developments such as new town development and road construction. Bare soil decreased by 3.35 km^2 for construction. In green-space area all land use types (forest, agricultural area, and water) decreased by 13.46, 17.74, and 0.96 km^2, respectively.

To understand the impact on SRT of land-use change, SRT change was derived for each land-use type. In the Mt Daemo area the overall mean SRT increased by 1.01°C from 1987 (25.17°C) to 1999 (26.18°C). The mean SRT decreased the most, by 4.22°C, where bare soil was changed into forest. For both forest areas between 1987 and 1999, SRT decreased by 0.17°C. This means that the forest was not disturbed and evapotranspiration increased because of the growth of vegetation. For both urban areas between 1987 and 1999, SRT increased by 1.42°C; this is indicative of the increase of urban structures and pavements. The SRT increase was especially large, 2.70°C, for change of an area from agriculture, because of the highly reflective vinyl covers. The SRT of bare soil also decreased because of shrinkage of the area.

In the Mt Gwanggyo area the overall mean SRT increased by 1.13°C from 1987 (23.10°C) to 1999 (24.23°C). The mean SRT decreased the most, by 5.97°C, where bare soil was changed into water, and the mean SRT increased the most, by 7.33°C, where water was changed into bare soil. For both forest areas between 1987 and 1999, SRT increased by 0.27°C. This means that forest was fragmented because of development and road construction. For both urban areas between 1987 and 1999, SRT increased by 1.70°C, indicative of the increase of urban structures and pavements. In terms of SRT change, forest and agricultural area increased by 0.15 and 0.16°C because of the

Table 3 Land-use change and the corresponding mean SRT change

			Land use (1987) in Mt Daemo area						Land use (1987) in Mt Gwanggyo area					
			Green			Non-green		Whole area (mean SRT)	Green			Non-green		Whole area (mean SRT)
			Forest	Agriculture	Water	Urban	Bare soil		Forest	Agriculture	Water	Urban	Bare soil	
Land use (1999)	Green	Forest	10.0 (−0.17)	1.12 (−0.55)	0.05 (+1.11)	0.47 (−1.80)	0.08 (−4.22)	11.74 (21.82)	91.90 (+0.27)	3.27 (−0.15)	0.16 (+1.27)	2.42 (−1.83)	0.05 (−3.69)	97.80 (21.56)
		Agriculture	0.48 (+1.01)	1.09 (+0.26)	0.02 (+1.79)	0.76 (−1.01)	0.21 (−3.66)	2.56 (24.47)	5.19 (+1.03)	4.06 (+0.52)	0.04 (+1.95)	3.54 (−0.76)	0.27 (−2.83)	13.10 (24.30)
		Water	0.03 (+2.10)	0.24 (+0.62)	0.17 (+1.00)	0.21 (−1.19)	0.01 (−4.11)	0.66 (24.46)	0.04 (+0.42)	0.03 (−0.55)	0.53 (+1.69)	0.20 (−0.50)	0.01 (−5.97)	0.81 (20.67)
	Non-green	Urban	1.53 (+3.79)	5.58 (+2.63)	0.15 (+4.16)	18.94 (+1.42)	3.75 (−0.85)	29.95 (27.91)	13.58 (+3.51)	22.90 (+2.98)	1.02 (+5.06)	32.86 (+1.70)	5.08 (−0.22)	75.44 (27.55)
		Bare soil	0.02 (+1.94)	0.17 (+3.78)	0.00 (+5.43)	0.20 +2.72)	0.08 (−0.83)	0.47 (28.83)	0.55 (+6.28)	0.58 (+5.19)	0.02 (+7.33)	0.91 (+3.75)	0.24 (+1.60)	2.30 (29.88)
		Facility agriculture	0.22 (+0.22)	1.46 (+2.70)	0.02 (+4.10)	1.25 (+1.77)	0.18 (+0.35)	3.13 (27.35)	–	–	–	–	–	–
	Whole area (mean SRT)		12.30 (21.91)	9.66 (24.48)	0.41 (22.35)	21.83 (26.60)	4.31 (29.05)		111.26 (21.41)	30.84 (24.14)	1.77 (20.79)	39.93 (26.30)	5.65 (28.90)	
Changed area (mean SRT change)			−0.56 (−0.09) −7.41	−7.10 (−0.01)	+0.25 (+2.11)	+8.12 (+1.31) +7.41[a]	−3.84 (−0.22)	48.51 (+1.01)	-13.46 (+0.15) −32.16	−17.74 (+0.16)	−0.96 (−0.12)	+35.51 (+1.25) +32.16	−3.35 (+0.98)	189.44 (+1.13)

Land-use changes are given in kilometers and the corresponding mean SRT changes are given in degrees Celsius in parentheses
[a]Including facility agricultural area in 1999

fragmentation and shrinkage of forest. With regard to land-use types, the SRT value is highest for bare soil and urban, followed by agriculture, forest, and water. This result was the same as that of Park's (2001) study.

In terms of SRT change in the Mt Daemo area, the SRT increased the most, by 12.46°C, at the Agricultural and Marine Product Wholesale Market at Garak-dong, Songpa-gu, because the surface material stored solar energy. The SRT decreased the most, by 7.80°C, at the tributary merging point of Tahn Stream, because the quantity of water was increased by tributary merging. The SRT decreased by 1.35–3.13°C inside the forest area (peak area of Mt Daemo and Mt Guryong) because of vegetation growth in the well preserved forest. Figure 2 shows where SRT decreased and NDVI increased in the Mt Daemo area. This is indicative of a decrease of SRT combined with an increase of vegetation index because of increased evapotranspiration. For water bodies, the SRT of both streams decreased. At Tahn streamside, SRT decreased by 6.91°C, because of the growth of vegetation (Fig. 2A). At Yangjae Stream, SRT was lower than in the surrounding area by 1.1–5.7°C. SRT was especially reduced, by 5.22–5.67°C, at Yangjae Streamside in front of the Residential Apartment site (Fig. 2B). The SRT mitigation effect of Yangjae Stream ranged from 120 to 300 m. This could be because of the increase of riparian vegetation after the natural style urban stream restoration project in the mid-1990s and green area in urban neighborhood parks such as Gaepo East and Gaepo West Neighborhood Park and Dahlteo Neighborhood Park, and adjacent education facilities (Japanese Foreign School and Gyeonggi Girls' High School) (Fig. 2C). These results show that connection of green space is more effective for SRT mitigation. In the Yangjae Urban Forest (Fig. 2D) the decrease in SRT by 0.44–4.15°C is because of the change from agricultural area to urban area.

The SRT at Mt Gwanggyo area increased most, by 17.75°C, on the left side of the Seoul tollgate, because of urban development of the forest area. The SRT decreased most, by 8.67°C, at the construction site of a commercial facility (large discount store at Suwon City). The SRT increase was especially large, 10–15°C, at Anyang City, Bundang, and Suji, and for the change to urban or bare soil from forest area at Mt Gwanggyo, because of urban expansion and land-use changes. The SRT of the northern forest area of LG Village (apartment site at Shinbong-dong, Suji) decreased by 8.97°C, because of restoration of vegetation after a forest fire.

Figure 3 shows where SRT and NDVI changed in the Mt Gwanggyo area. The figure shows an increase of SRT combined with a decrease of vegetation index, because of urban expansion and road construction. SRT in the core area within the forest increased by 0.45–1.82°C, because of forest fragmentation and road construction, for example the Seoul beltline highway, the Shingal–Ansan highway, and the Gwacheon–Uiwang expressway.

Figures 3A and 3B show the slope cutting along the valley for residential development. Figure 3C shows the serious forest shrinkage resulting from large-scale residential development. The SRT increase was especially large, 4.17–10.92°C, at the oil gas storage facility construction site, as shown in Fig. 3D.

An attempt was initially made to match AWS data and TM-derived SRT. The R^2 value from regression analysis revealed a poor relationship between these data, however. To verify the SRT results, mean values of SRTs and AWS temperatures were compared. Mean SRTs were higher than AWS temperatures by 3.21°C (SRT: 23.74°C, AWS: 20.53°C) and 3.33°C (SRT: 23.66°C, AWS: 20.33°C) in the Mt Daemo and Mt Gwanggyo areas, respectively. According to Jo et al. (2001a) the difference between the SRT and AWS data was 1.5–2.0°C. In another study by

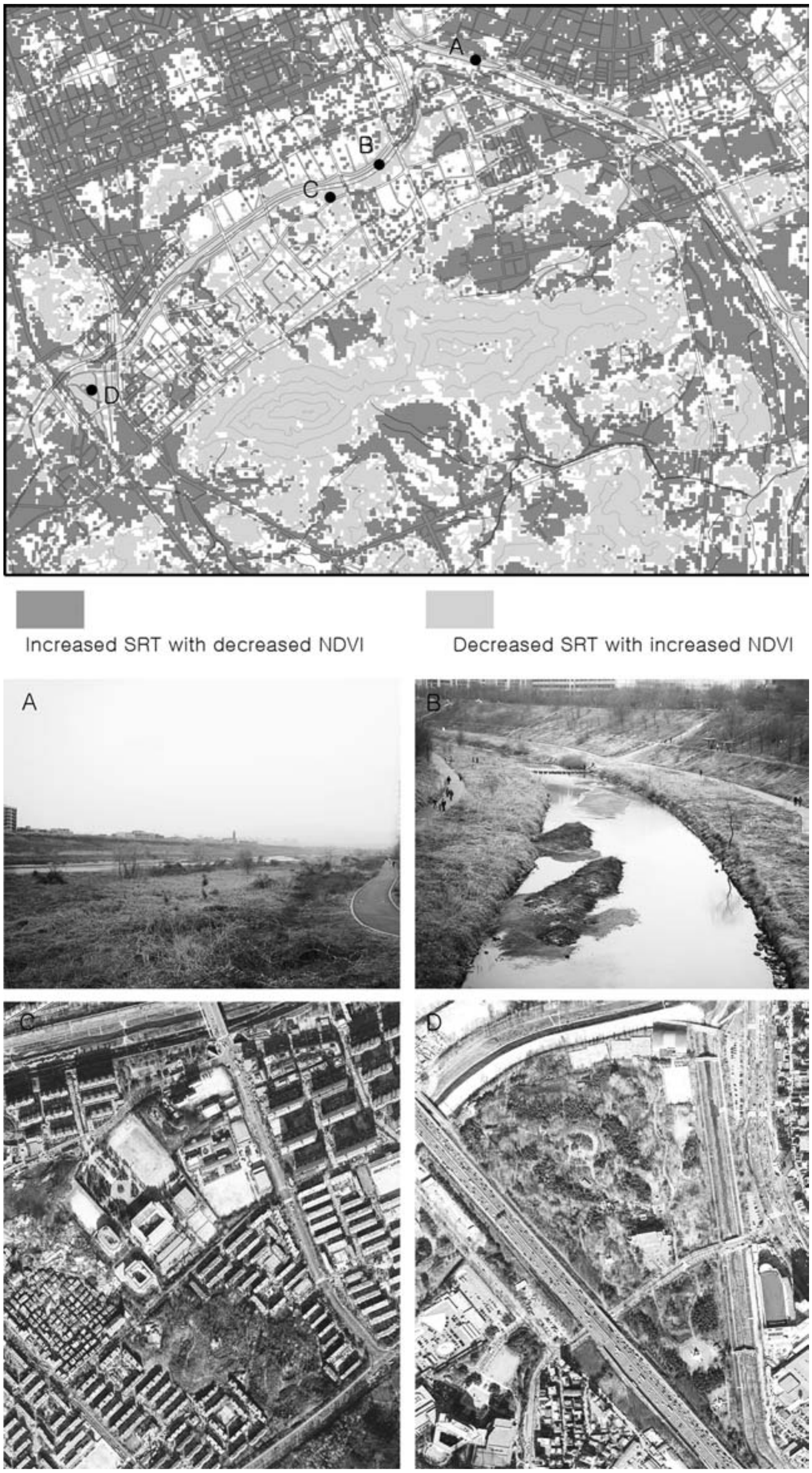


Fig. 2 Reduced SRT and increased NDVI in the Mt Daemo area

Jo et al. (2001b), the difference between them was 2.2 ± 0.2°C whereas in Park's (2001) study the difference was 3.3–4.3°C. Emissivity was not corrected in the studies of Jo et al. (2001a, b), however, but was in that of Park (2001). Taking into consideration emissivity correction and seasonal difference, Park's (2001) results are similar to those in this study. Overall SRT was higher than ground-measured temperature.

Conclusions

Although the areas south of Seoul in Korea are rapidly expanding and urbanizing, existing studies have not covered these areas. A combined approach of RS and GIS was therefore used to estimate urban green space SRT change in the rapidly expanded area. Urban SRT

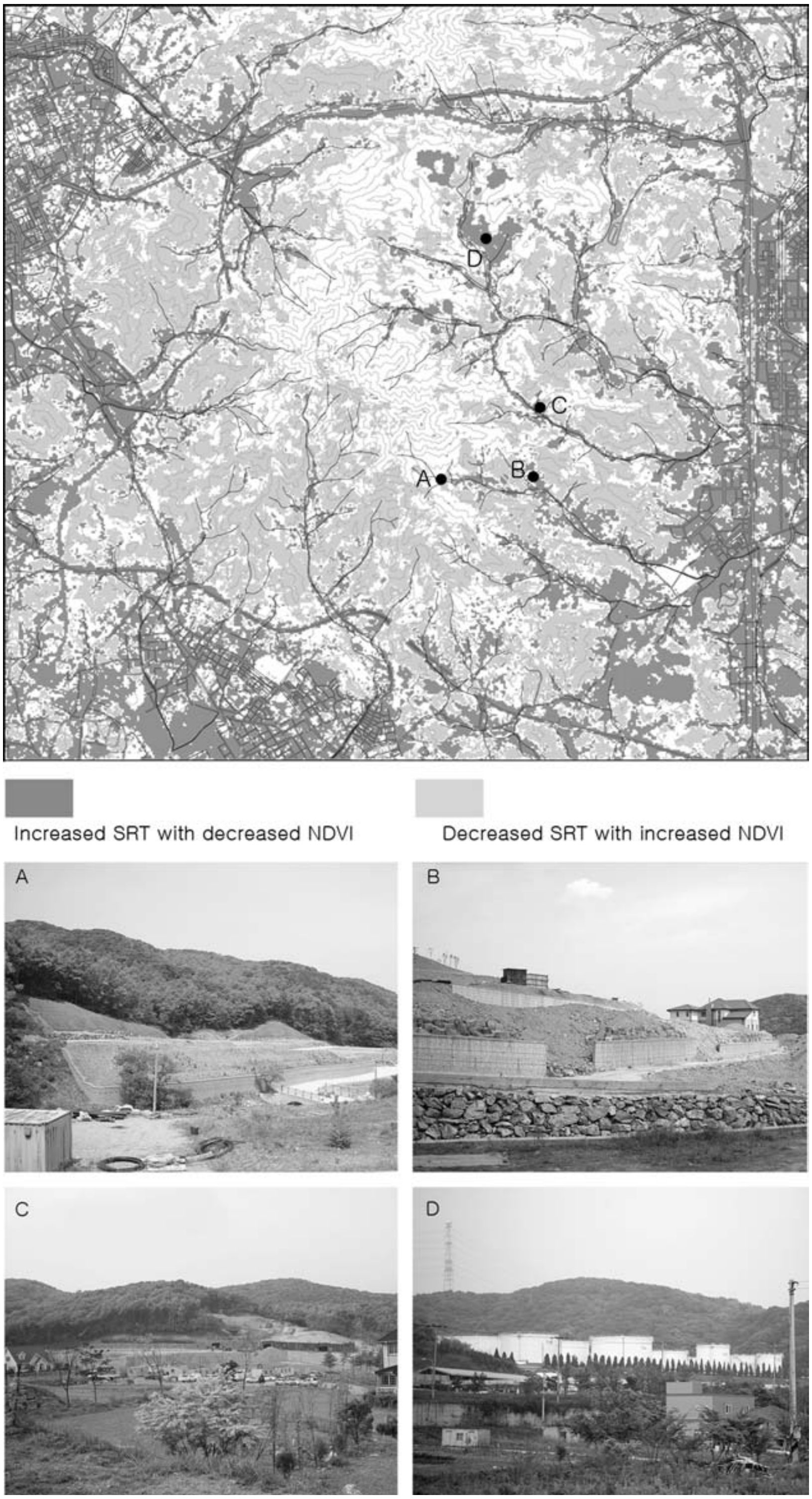


Fig. 3 SRT change with NDVI change in the Mt Gwanggyo area

increased as green space was converted into non-green-space area. Also, well preserved green space, especially newly connected green space, contributed to a decrease of SRT. The following conclusions were derived:

1. In the Mt Gwanggyo area, forest and agricultural areas decreased by 13.46 km^2 and 17.74 km^2, respectively, because of urban expansion and road construction. In the Mt Daemo area, forest and agricultural areas decreased by 0.56 and 7.10 km^2, respectively, because of urban expansion.
2. SRT increased overall by 1.13 and 1.01°C in the Mt Gwanggyo and Mt Daemo areas, respectively, from 1987 to 1999.
3. The SRT decreased by 1.35–3.13°C in the Mt Daemo forest area because of vegetation growth whereas the SRT increased by 0.45–1.82°C in the Mt Gwanggyo forest area because of new town development and road construction. This result suggests that growth of vegetation in well preserved green space is important in urban SRT mitigation and that proper management of urban green space is very important in maintaining SRT.
4. Connection of green space proved an effective means of urban SRT mitigation.

This study confirmed the importance of effective management and arrangement of urban green space for urban SRT mitigation. Ultimately, urban green space SRT change should be considered in urban planning.

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