Are New Residential Areas Cooler than Older Ones?

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Abstract

This study was conducted to investigate if passive cooling technologies have been implemented in commercially supplied new residential areas in Bangkok and to observe if there were significant differences in the land surface temperature (LST) compared to old residential areas. Values of LST were compared among 62 residential areas that differed in completion year. The mean LST for the most recent residential areas completed in 2013 or later was significantly less than that for the other older categories, suggesting that passive cooling effects were significantly better functioning in the new residential areas. A roof treatment on old buildings in a public housing project was still quantitatively effective after 8 years. This suggested the possibility of a deteriorated cooling function in the older categories among the residential areas. The possibility of deterioration was quantitatively investigated. The results stressed the importance of the periodic maintenance of passive cooling functions. As an extension of precise basic studies, this is the first study to quantify the passive cooling effects on commercially supplied residential areas. In terms of spatial extent, this residential area–scale study bridges precise analyses of single buildings/materials and regional observations, mainly relying on satellite data. The study results can aid in the mitigation and prevention of the urban heat island phenomenon.

1- Introduction

The earth is becoming hotter every day. Especially under warm/summer and tropical climatic conditions, it is growing increasingly challenging to obtain thermal comfort. In hot conditions, the use of air conditioners is becoming common, although these make the environment even hotter and generate more carbon dioxide, which further increases global warming. To cope with this warming, passive cooling is a sound approach to achieving thermal comfort with no or minimal energy consumption [1]. Passive cooling includes multiple technologies. Among them, radiative and reflective cooling processes minimize the absorption of heat [2]. An example is applying a roof color that prevents solar heat gain [3]. Raising roof reflectivity from 10 to 20% to 60% reduced cooling-energy use in buildings by more than 20% [4].

In many cities, including those with tropical and warm climatic conditions, urbanization is taking place due to social and natural demographic changes. Because urbanization results in an increase in land surface and air temperatures in the area [5], applying passive cooling technologies to urban areas is expected to be a sustainable countermeasure. Passive cooling technologies have not been well investigated in real urban settings, however, and the extent to which they have been employed there to mitigate harsh and uncomfortable conditions is unknown. To date, passive cooling technologies have been intensively examined and evaluated in terms of their economic aspects [1], new materials for cooling (especially phase change materials) [6, 7], structures involving plant bodies on rooftops and walls [8], and structures for effective ventilation [9]. The examination and evaluation of passive cooling technologies described in the latest review articles led us to theoretical generalizations, such as reduced energy consumption for active cooling [10]. Passive cooling

examples in single buildings and houses have been described in experimental settings [11]. These well-controlled settings enable the precise and accurate measurement of passive cooling effects, as demonstrated by Al-Yasiri and Szabó [12]. It is of note that there have been no reports that examine and evaluate passive cooling effects in actual commercially established residential areas. One experiment involved the construction of a 1:10 scaled miniature town to observe heat absorption in the town [13].

To resolve the uncertainty surrounding the application of passive cooling technologies in real urban settings with warm/summer and tropical climatic conditions, this study investigated if new residential areas in Bangkok are cooler than older ones. Bangkok is the capital of Thailand, where the socio-economic profile is rapidly changing. Human migration to the capital [14] has resulted in a demand for more houses. Many new residential areas have been constructed over the past two decades (Figure 1, [15]). In this study, relatively new and old residential areas were compared in terms of land surface temperature (LST) in February 2022.
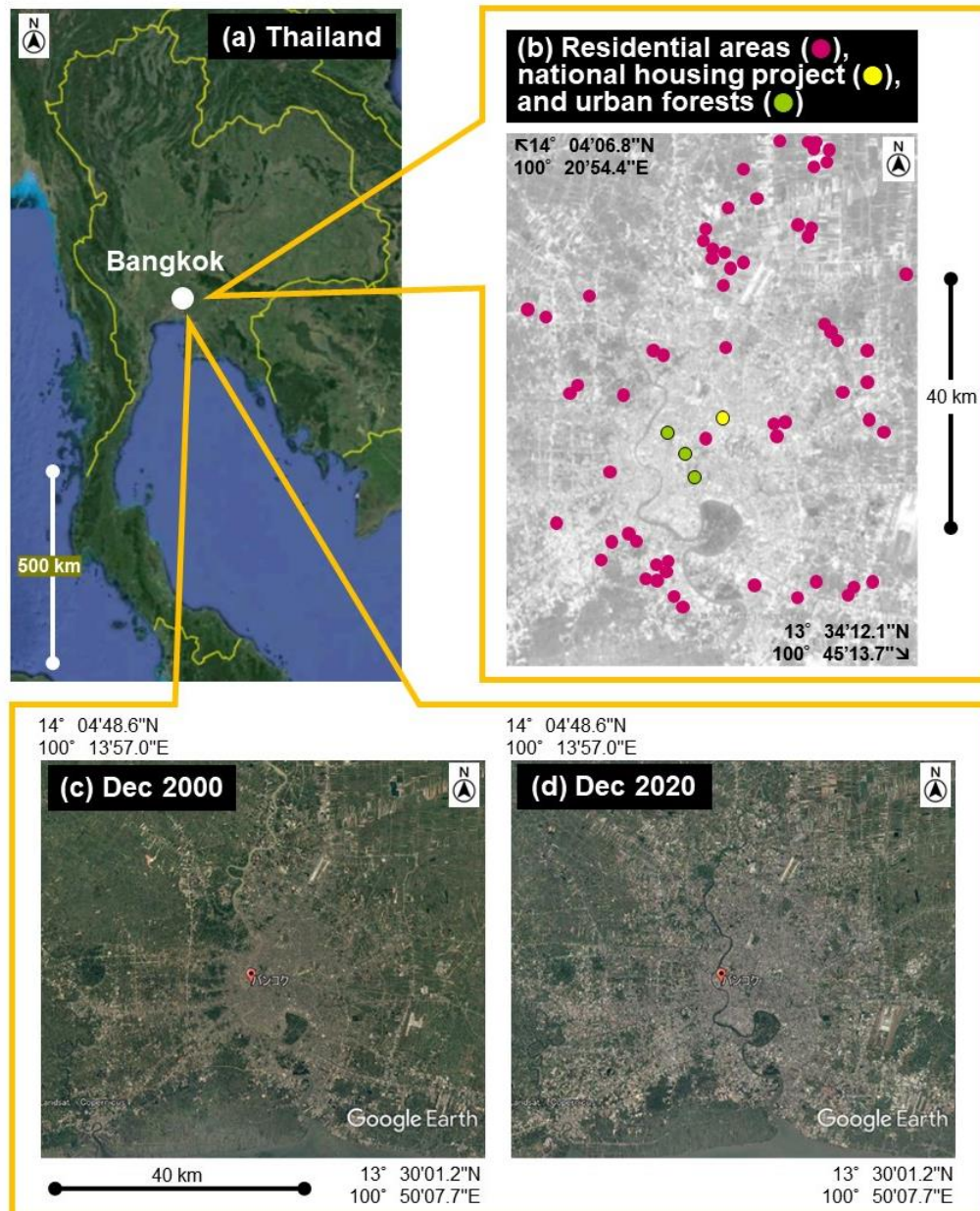

Figure 1. Maps of Thailand (a), positions of the Bangkok residential areas investigated in this study (b), and true-color aerial images of Bangkok and surrounding provinces in 2000 (c) and 2020 (d)

By extending the above comparison of new and old residential areas in Bangkok, the effects of a roof treatment of old buildings in a public housing project were quantified. The results suggest the possibility of deterioration effects on the passive cooling function in some residential areas and the possibility was quantitatively investigated. This is the first study to quantitatively investigate if new residential areas are cooler than old ones. To the best of the authors' knowledge, this is the first study to investigate the loss of cooling effects in residential areas between 2013 and 2022.

2- Methods

2-1- Site Description

Sixty-two residential areas, three urban forests, and the Huai Khwang national housing area in Bangkok (Figure 1) were selected. The climate is classified as savanna [16]. The 62 residential areas were randomly selected from those visually recognized in the latest aerial images. The urban forests were selected as references for the comparison of LST values between the forests and the residential areas. The three forests were located in Lumpini Park, the Chitralada Royal Villa, and the Queen Savang Vadhana Museum. The buildings of Huai Khwang national housing program underwent roof treatment in 2014.

The years of completion of construction were confirmed using Google Earth Pro (Google Inc., CA, USA). The Huai Khwang national housing buildings have five storeys, while the other residential areas have one to five storey(s). The smallest area was represented by a 3×3 pixel square in the Landsat imagery of 30×30 m resolution. Thus, the areas were 90×90 m or greater.

2-2- Landsat 8 Imagery for Land Surface Temperature Determination

Remote sensing imagery datasets acquired by the Landsat 8 Operational Land Imager were used. The datasets used in this study were acquired on 20 April 2013, 2 February 2014, 12 April 2016, 22 March 2020, and 24 February 2022. The datasets were acquired between 10:37 and 10:39AM, local time. Among these datasets, the 2022 imagery was used for the comparison of the 62 residential and the other areas. The flowchart of the research methodology that was used to achieve the study's aims is shown in Figure 1.

The datasets were level-1 products to which had been applied geometric corrections. Images for band 4 (red, central wavelength 655 nm), 5 (near-infrared, 865 nm), and 10 (thermal infrared, 10895 nm) were used. DOS1 atmospheric correction of values carried by the pixels was conducted using QGIS 3.20.3 (Free Software Foundation, Inc., MA, USA). LST values were determined for the 30 m × 30 m resolution pixels applying the method proposed by Valor and Caselles [17], which performed well in southern Vietnam where similar climatic conditions and vegetation types exist [18]. The equation was also useful in the drier land of Yazd, Iran [19]. To avoid pixels being significantly affected by cloud, cloud shadow, and other uncertainties, this study utilized quality assessment images with the aid of the QGIS software.

The difference in LST between a residential area and the urban forest was determined as:

$$LST_{resid-forest} = LST_{resid} - \sum(LST_{forestN})/3 \qquad (1)$$

where, LST_{resid} and $LST_{forestN}$ are the mean LST (°C) for the pixel representing the residential area and that for pixels representing the N-th forest. Because pixels representing the three urban forests were used, the sum was divided by three.
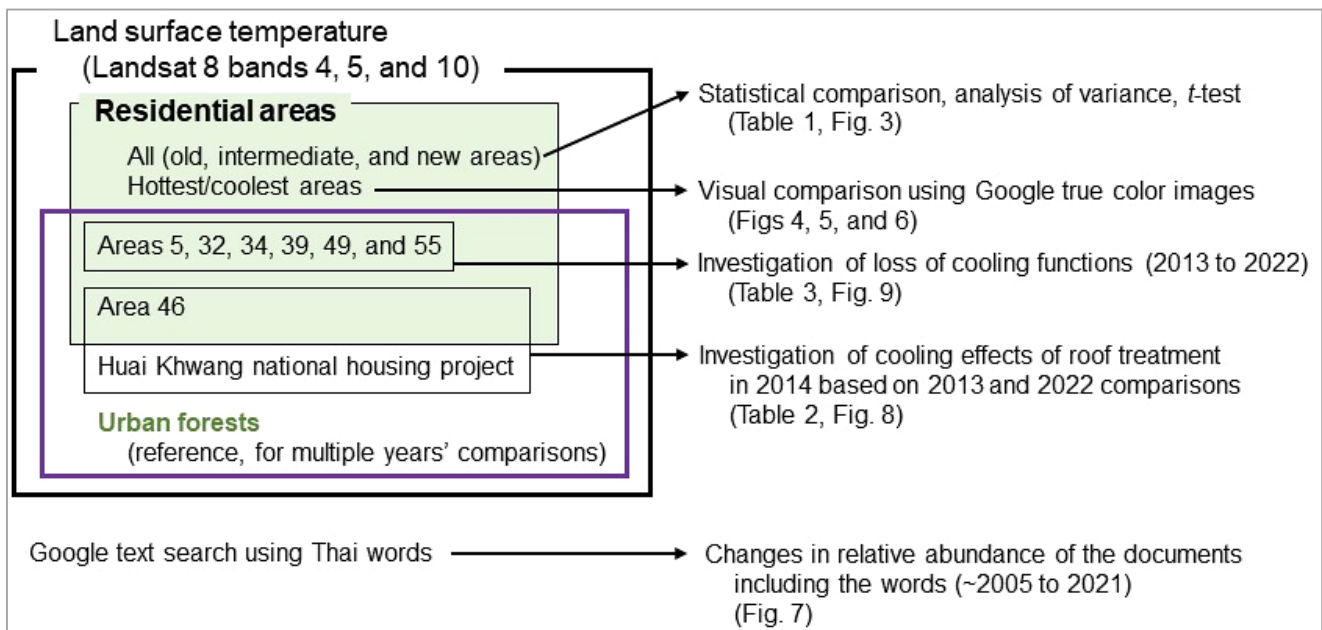

Figure 2. Flowchart of this study

2-3- Statistical Analysis

XLStat version 2021.4.1 (Addinsoft Inc., Paris, France) was used for statistical analyses. Analysis of variance was performed to compare housing areas of different completion years in terms of LST. In determining values of standard deviation, the n-1 calculation method was selected. As a post hoc *t*-test, the Bonferroni *t*-test was used. A two-tailed paired *t*-test was performed to evaluate the significance of the observed differences before and after painting the roofs of the buildings of the Huai Khwang national housing project. Analysis of variance was also performed to examine the significant differences among housing areas and years on the efficiency of passive cooling.

2-4- Google Document Search

Google was used to find documents that included keywords. The number of cooling-related documents was determined simultaneously using "หลังคา (*langkaa*, roof)," "เย็น (*yen*, cool)," and "วัสดุ (*wasadu*, material)." Likewise, the number of more general documents was determined simultaneously using "อาหาร (*aahaan*, food)," "อร่อย (*aroy*, tasty)," and "สุขภาพ (*sukhaphaab*, health)." The document publication years were limited to single years between 2011 and 2021, a period of 2005 or before, and a five-year period of 2006 to 2010.

3- Results

3-1- Comparison of the 62 Residential Areas

Figure 3 indicates that, at the 24 February 2022 time point, the most recent residential areas tended to be cooler than the other residential areas. The 2004 or earlier areas were hot. Among the 62 residential areas, the years of completion could not be identified in 4. Instead, they were determined to have been completed between 2005 and 2012. Given this, the 62 residential areas were categorized as follows: oldest (completion in 2004 or before), newest (2013 or later), and in between (2005–2012).
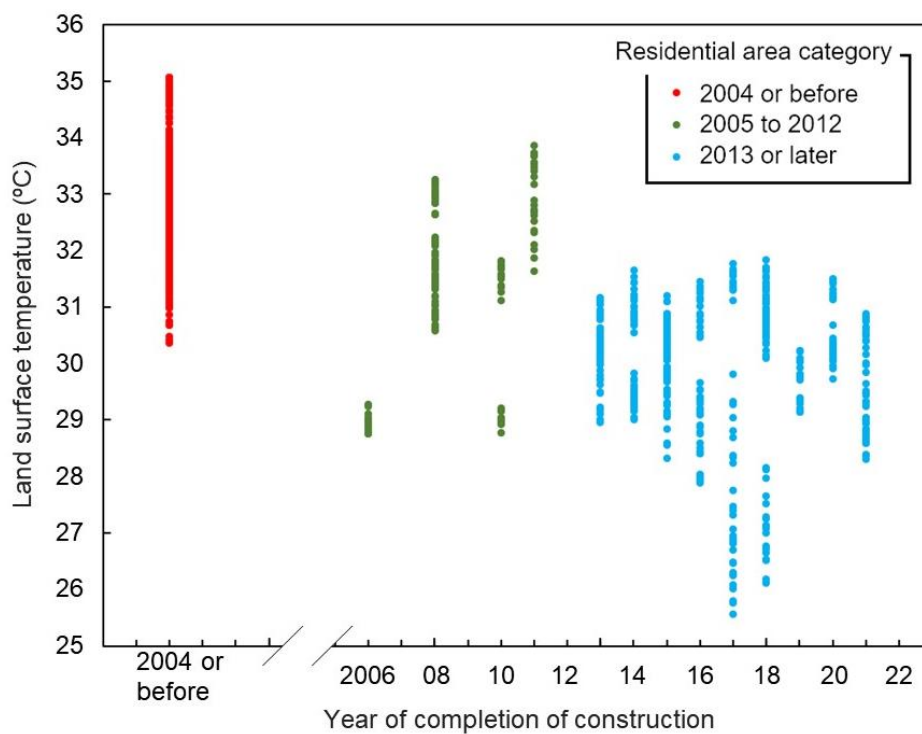

Figure 3. Values of land surface temperature for all pixels representing the residential areas completed in 2021 or earlier in the Bangkok region. For some areas, the precise completion years could not be identified although the areas were completed between 2005 and 2012. For these areas, land surface temperature values are shown as those for the 2008-completed areas.

Analysis of variance showed that the category of residential area was significant as a source of variation of LST ($p < 0.0001$, Table 1). LST differed significantly ($p < 0.0001$) among the years of construction completion. As shown in Figure 4, the hottest residential area had a mean LST of 34.6°C (standard deviation 0.4°C) while the coolest had a mean LST of 26.6°C (standard deviation 0.6°C). The construction of the hottest residential area was completed before 2005. The coolest residential area was completed in 2017. The appearance of the hottest area was visibly different from the coolest in that the roofs and roads were darker. The same contrast was observed for the second and third hottest/coolest residential areas (Figure 5).

Table 1. Mean land surface temperature for the residential area categories

Residential area category	Number of pixels	Mean (°C)	Standard deviation (°C)	Significance (*p* value)		
				2004 or before	2005–2012	2013 or later
2004 or before	424	33.0[a*]	0.9	Not applicable	< 0.0001	< 0.0001
2005–2012	125	31.5[b]	1.5	< 0.0001	Not applicable	< 0.0001
2013 or later	459	29.9[c]	1.3	< 0.0001	< 0.0001	Not applicable

[*] Means indexed by different letters differ significantly according to the Bonferroni *t*-test ($p < 0.0001$).

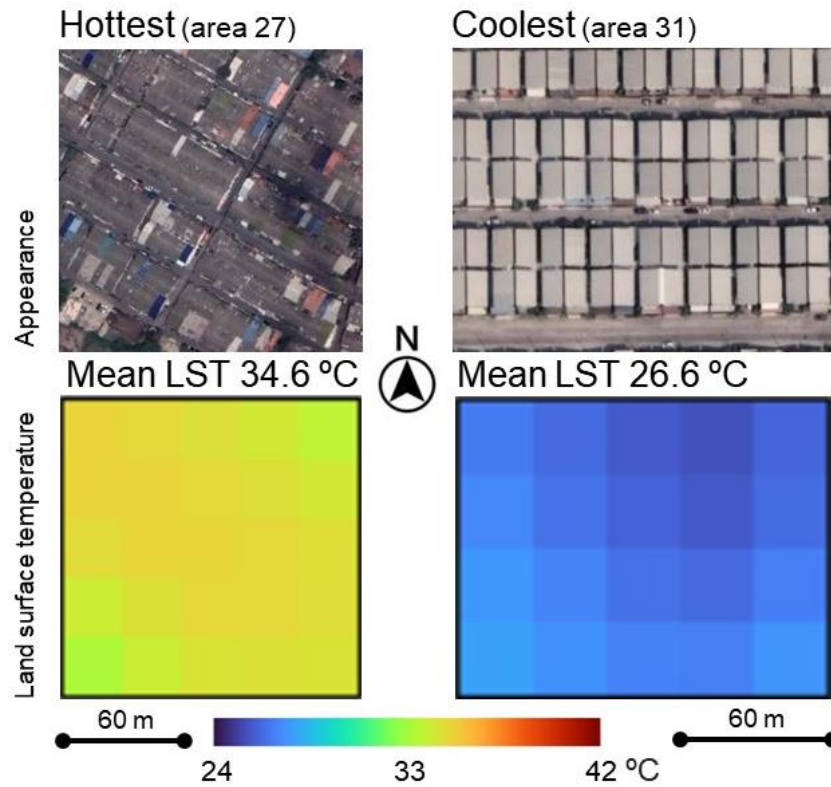**Figure 4. Appearance of the hottest and coolest of the 62 residential areas (top) and land surface temperature (bottom). The true-color images (top) were acquired in 2021**
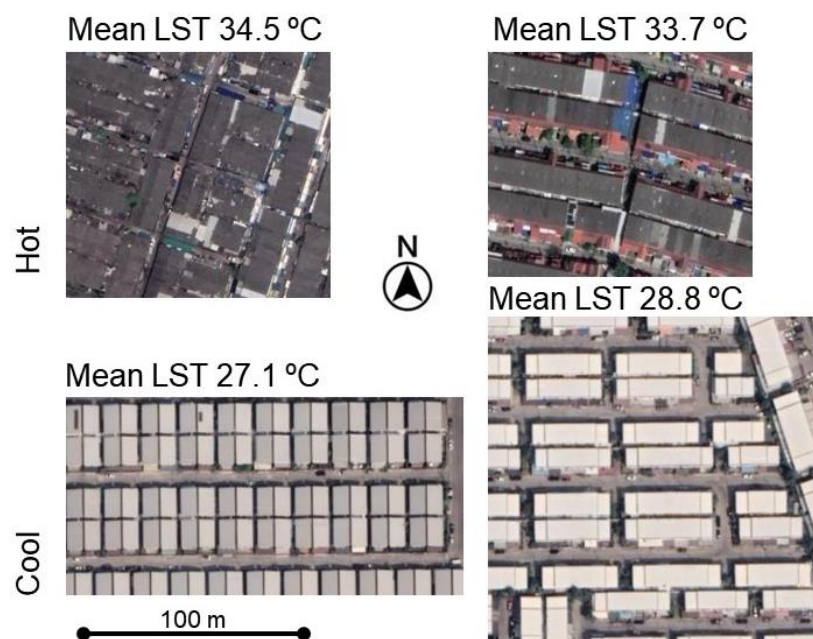

Figure 5. Second coolest/hottest (left) and third coolest/hottest (right) among the 62 residential areas. The images show the 2004 or before (top) and the 2013 or later (bottom) residential areas. The images were acquired in 2021

In addition to color, differences in material are also perceivable in the images (Figures 4 and 5). As shown in Figure 6, in the past, wavy slate was widely used as a roofing material. Roads also differ in material and color.

Figure 6. Google street view of the hottest residential area (area 27, Figure 4) in March 2022. Wavy slate is widely used as the roofing material. The roads are covered with asphalt

3-2- Human Recognition and Adoption of Passive Cooling

The differences between the oldest and newest housing areas are believed to be associated with the results of the Google document search (Figure 7). In the 2000s and before, the relative abundance of roof cooling–related documents was low. The ratio of cooling-related document abundance increased in the early 2010s, peaked in 2017, and dropped again.
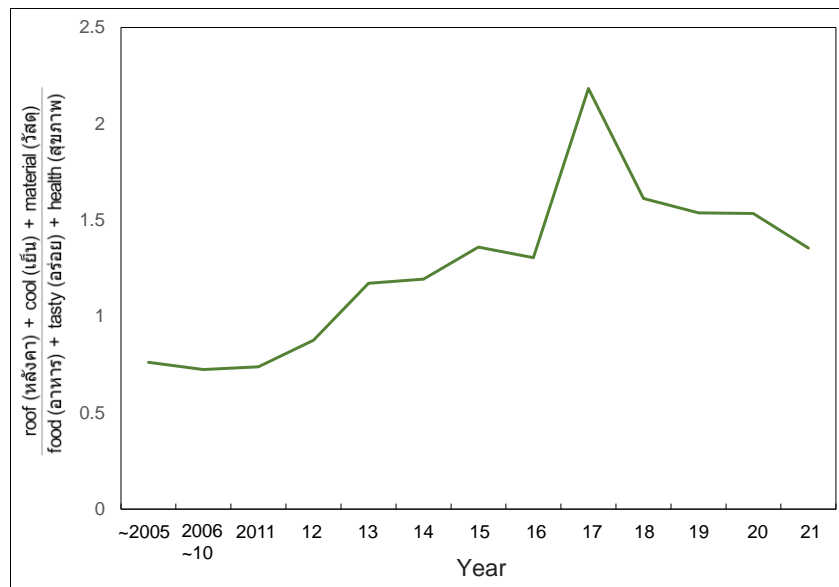

Figure 7. Relative abundance of roof and cooling-related documents based on a Google document keyword search

In 2014, when passive cooling technologies were becoming popular (Figure 7), the national housing project underwent a roof treatment. In 2013, before the roof treatment in 2014, the national housing area was 5.2°C hotter than the urban forests (Table 2). The closest residential area 46 was compared in terms of LST. Residential area 46 was one of the oldest among the 62, and already existed in 2002 according to Google Earth Pro. The visual appearance was close to that of the hottest residential area in Figures 4 and 5, revealing dark-colored roofs and roads. At the 2013 imagery acquisition time, residential area 46 was 8.0°C hotter than the urban forests. This $LST_{resid-forest}$ value was almost the same in the 2022 Landsat data acquisition time when the national housing area had an $LST_{resid-forest}$ value of 3.7°C. This decrease from 5.2°C was highly significant ($p < 0.0001$, Figure 8) while the change in $LST_{resid-forest}$ value was much less significant ($p = 0.022$) for residential area 46. Therefore, the cooling effect of the roof treatment in 2014 remained pronounced in 2022 in the national housing residential area. The treated roof area was only 25.1% of the entire area represented by the 158 pixels. However, the cooling effect was significant for the entire area.

Table 2. Effects of 2014 roof treatment on land surface temperature in the national housing area of Huai Khwang district. As a reference, the closest residential area (area 46) among the 2004 or before housing areas was compared

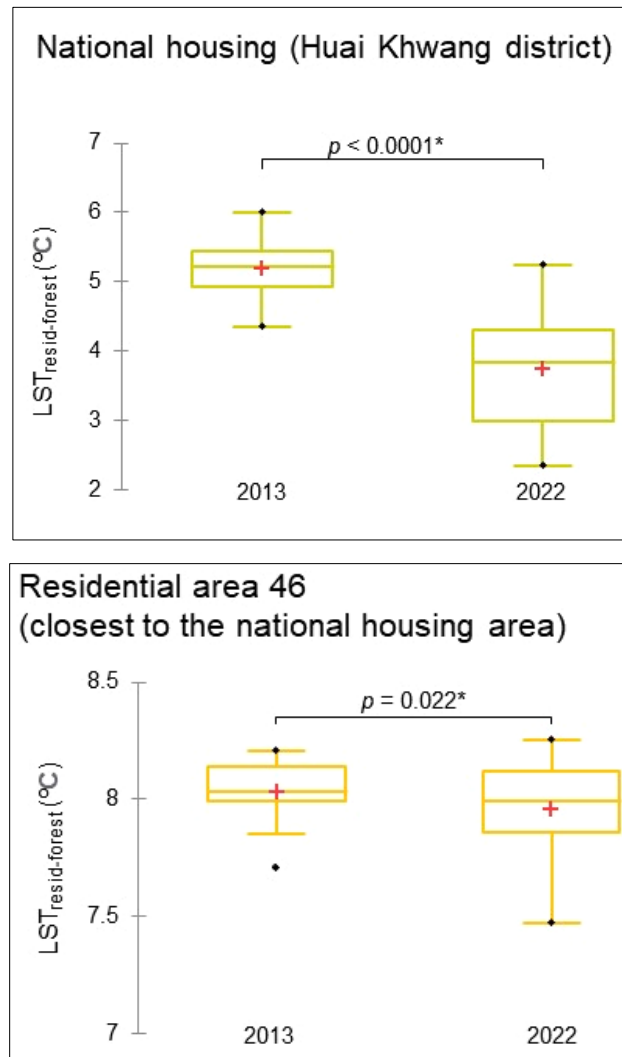| Area		Number of pixels	20130420		20220224	
			Mean (°C)	Standard deviation (°C)	Mean (°C)	Standard deviation (°C)
Residential	National housing	158	35.0	0.4	30.3	0.8
	Residential area 46	16	37.8	0.1	34.5	0.2
Urban Forests	Lumpini	18	29.6	0.4	26.6	0.2
	Museum	23	30.2	0.3	26.4	0.2
	Chitralada	53	29.5	0.2	26.7	0.2

Figure 8. Results of the paired *t*-test to examine the significant difference in LST$_{resid-forest}$ (°C) between 2013 and 2022. The buildings in the area of the national housing project in Huai Khwan district underwent roof treatment in 2014. The bottom diagram indicates changes in LST$_{resid-forest}$ (°C) in residential area 46. The top and bottom of the box indicates the 25 and 75 percentile values, respectively. The red cross indicates the mean. The black dot indicates an outlier.

3-3- Investigation of Deterioration Effects

As demonstrated by the example of the national housing project, roof cooling treatments are worthwhile because they reduce the LST, which is significantly associated with room temperature and thus, electricity consumption. Here, a question arises. Did the 2005 to 2012–completed residential areas lose their cooling function over time? To investigate this possibility, the 2005 to 2012 residential areas were analyzed. Table 3 indicates the changes in LST within the 2013 to 2022 period in six residential areas completed between 2005 and 2012. There were two more residential areas, but their LST values were unavailable for some years due to an unknown computer glitch. Among the six areas, residential area 32 was the hottest in 2016 when an extreme weather anomaly was observed in Southeast Asia [20], including Thailand [21]. The 2022 acquisition time was the coolest.

Table 3. Land surface temperature between the 2013 and 2022 Landsat 8 data acquisition times for selected 2005 to 2012–completed residential areas and urban forests as the references

Area		20130420		20140202		20160412		20200322		20220224	
		Mean (°C)	Standard deviation (°C)	Mean (°C)	Standard deviation (°C)	Mean (°C)	Standard deviation (°C)	Mean (°C)	Standard deviation (°C)	Mean (°C)	Standard deviation (°C)
Residential	5	32.6	0.3	30.9	0.1	33.9	0.1	31.8	0.2	29.0	0.1
	32	31.6	1.1	33.4	0.3	38.2	0.1	35.1	0.2	33.6	0.2
	34	34.7	0.1	32.6	0.1	37.3	0.1	33.5	0.2	32.9	0.2
	39	33.2	0.2	31.8	0.2	37.2	0.2	32.8	0.2	31.5	0.2
	49	31.0	0.3	29.6	0.3	34.6	0.3	31.3	0.1	29.0	0.2
	55	33.1	0.2	31.9	0.3	37.1	0.3	32.9	0.4	31.8	0.3
Urban Forest	Lumpini	29.6	0.4	28.0	0.3	31.5	0.3	28.5	0.2	26.6	0.2
	Museum	30.2	0.3	28.4	0.3	31.6	0.4	27.8	0.4	26.4	0.2
	Chitralada	29.5	0.2	27.9	0.2	30.8	0.2	28.9	0.3	26.7	0.2

Based on the values in Table 3, $LST_{resid-forest}$ values were determined for the six residential areas at the timepoints between 2013 and 2022 (Figure 9). Analysis of variance resulted in $p < 0.0001$ for both year and residential area; thus $LST_{resid-forest}$ significantly fluctuated over the 10-year period and among the residential areas. For residential areas 32, 34, 39, and 55, in the later years, a tendency to become hotter was revealed. In contrast, residential area 5 was constant in terms of $LST_{resid-forest}$ within the decade. Residential area 49 experienced an increase in $LST_{resid-forest}$ at one point but achieved a decrease in $LST_{resid-forest}$. Residential area 32 clearly lost its cooling function. At the 2013 timepoint, LST values for area 32's pixels showed large intra-variation among them. This suggests that residential area 32 was indeed losing its cooling function which used to cover the area.
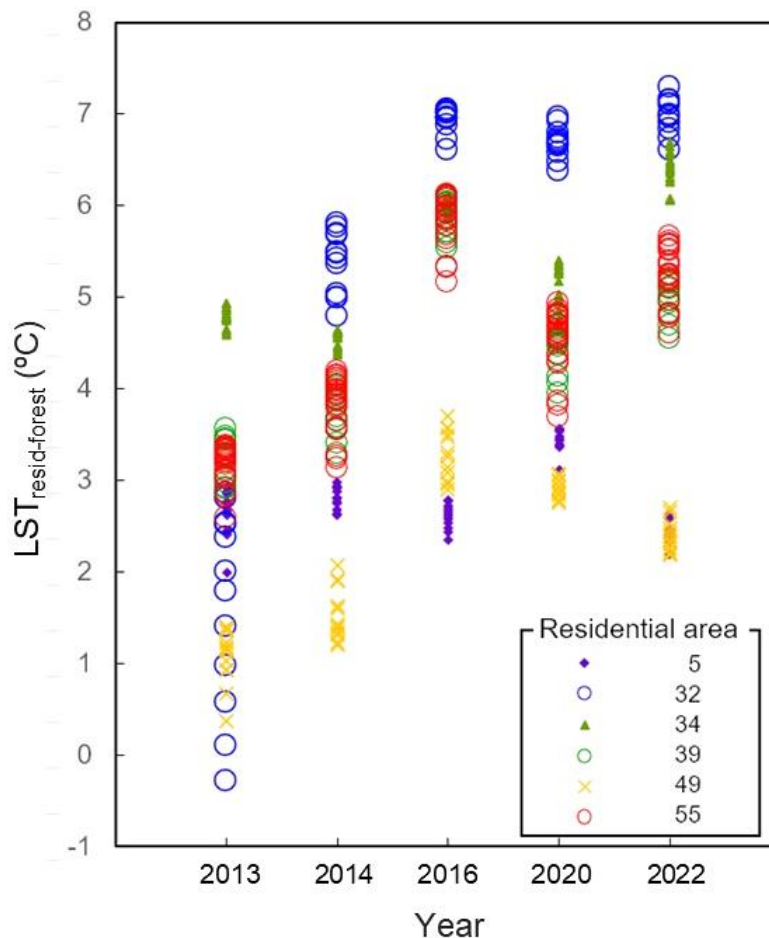
Figure 9. Changes in $LST_{resid-forest}$ (°C) for six residential areas completed between 2005 and 2012

4- Discussion

4-1- Main Findings

This is the first study to demonstrate that new residential areas were cooler than older ones in the same region, indicating the application of passive cooling technologies to new houses, roads, and other components. The application of a roof treatment to the national housing project was retaining significant cooling effects even 8 years after the treatment. This national housing project result suggests that older residential areas experienced a deterioration in passive cooling effects. This hypothesis was demonstrated by comparing residential areas of different completion years. These findings indicate the importance of the periodic maintenance of the passive cooling functions of roofs, roads, and other components in residential areas.

4-2- Comparison with Other Studies

This study extended the established basic knowledge described in the latest review articles [1, 6-9], which summarized the passive cooling effects of materials and on single houses or buildings. In addition to this prospective nature, the findings in this study bridge pieces of knowledge related to precise house/building/material-scale experiments and regional analyses largely supported by remote sensing. Urban heat islands and suburban green areas have been intensively observed within 100 km^2 areas or greater regions [22]. The heat island phenomenon is elucidated by the current findings, which demonstrate the results of the precise passive cooling mechanisms generalized and systematized in the aforementioned review articles. Thus, residential area–scale cooling implementations such as rooftop treatments would be useful for urban heat island mitigation.

4-3- Implication and Explanation of Findings

It is very likely that, at the February 2022 data acquisition time in the hottest area, the roofs and roads absorbed more solar radiation than the coolest residential area [23]. It is evident that recently constructed residential areas employ more cooling measures than the older residential areas (Figures 4 and 5). The coolest three areas have light-colored roofing materials. In contrast, the hottest residential areas have dark-colored roofs. Asphalt roads were also recognized using Google Earth's street view function (Figure 6). In the hottest residential area (area 27), typical houses had wavy slate roofs. Material-wise, the coolest and hottest residential areas are visually very different. Various roofing materials are currently available in Bangkok. The materials differ in solar reflectance and accompanying solar energy absorption.

Passive cooling effects of color and physical structure have been precisely and accurately demonstrated. For example, Akbari et al. [4] analyzed various pigments in order to identify highly solar-reflecting pigments for roofing materials. Super white roofing material had a solar reflectance value of 60% while that of a black one was 5%. When the black material was exposed to light, it reached 82°C while the super white one was 53°C. The differences in the color of the roads and roofs shown in Figures 4 and 5 contribute to the differences in LST. On a summer day in Oak Ridge, Tennessee, USA, the air temperature of a small gap under a slate roof was approximately 50°C whereas that under a clay-type material was 43°C [24]. Similarly, different road materials exhibit different temperatures when exposed to solar radiation. In Sarawak, Malaysia, an asphalt road surface was 6°C hotter than a nearby concrete surface [25]. Differences in road material among the residential areas contribute to the temperature differences (Figures 4 to 6)

Regarding the changes in the appearance of documents on passive cooling technologies in the Internet space (Figure 7), a possible explanation is that up until the 2010s, roof materials for passive cooling became popular among some stakeholders and specialists, especially housing developers [26]. At the February 2022 timepoint, cooling materials for roofs and other parts were already highly recognized among builders. This assumption is reflected in the cooler residential areas completed in 2013 or later. Probably associated with the trends in the actual housing and material market, the number of papers on passive cooling research increased rapidly after 2000 [27].

In contrast, around 2010, passive cooling measures were not yet well recognized by the residents in the region. This behavior may be reflected in the finding that the relatively old residential areas continued to be hot despite opportunities for applying passive cooling technologies. In and around 2010, passive cooling was not yet popular among home buyers according to Yacoulby et al. [28]. Adhikari et al. [26] put forth that the Thai government should play an important role in disseminating information regarding passive cooling technologies, and it is of note that the Thai National Housing Authority implemented a roof treatment in 2014 (Figure 8).

Table 3 and Figure 9 demonstrates that depending on materials and other conditions, passive cooling effects may be well or poorly retained. Residential areas 32, 34, 39, and 55 become hotter. In these four residential areas, roads may have been darker. Also, the areas are largely occupied by roofs, which may have been affected by roof deterioration effects. According to Berdah et al. [29], there are several causes of roof deterioration. Among them, photodegradation, high temperatures, moisture, pollutants, biological growth, and soiling are common in Bangkok. Strong solar radiation can decompose surface materials, and then rain washes the fragments away. Dust deposition is nearly constant [30]. As a result, cooling effects and agents are easily disabled. The roofs are prone to become dark, mostly as a result of the

alluvial soil distributed in the lowland [31]. Dark roofs attract more solar radiation. These factors negatively affect the cooling effects of roofs. Hence, as the above results indicate, restoration measures every few years are needed. In Athens, three to four years after applying a cooling paint on a building roof, various signs of deterioration were revealed, such as visually perceivable corrosion of the surface, various microbial species, and, most importantly, a several degree Celsius higher surface temperature [32]. Some buildings of the Huai Khwan national housing project underwent a roof treatment in 2006, but the surface was obviously deteriorated until 2013 (Table 2). Thus, quality-wise, the 2014 treatment seemed to be better than the 2006 treatment.

4-4- Strengths and Limitations of This Study

LST values for the residential areas are efficiently retrieved from Landsat imagery data. A single scene of remote sensing imagery covers a wide area, such as 34,000 km^2 (Landsat 8). The Landsat 8 satellite provides imagery datasets with a resolution of 30 m and is thus suitable for obtaining LST values for residential areas. Also, the LST determination method is well-established, especially for Landsat imagery datasets [33]. For convenience and reliability, this satellite-supported measurement would be widely applicable to various residential areas around the world as long as remote-sensing imagery datasets are available. However, a clear limitation is that users do not retrieve accurate air temperature values, although LST and air temperature roughly correlate [34, 35]. To address this uncertainty, the accurate determination of passive cooling effects such as the reduction of electrical consumption is difficult. This limitation is, however, expected to be overcome by combining LST and actual air temperature values for residential areas and rooms. The best passive cooling technologies for each residential area would be drawn in terms of electrical consumption or similar measures that are significantly associated with human health [36]. Based on this information, employing an empirical approach, satellite-supported observation may more accurately evaluate the passive cooling effects.

5- Conclusions

Over the past two decades, passive cooling technologies have been intensively investigated for single houses/buildings and on precise material-level scales. This is the first study to extend the precise investigation of passive cooling effects to commercially supplied residential areas. Also, with regard to spatial extent, the current residential area–scale study connects the precise house/building/material-scale and region-scale studies, especially those on urban heat islands relying on satellite data. Though LST correlates to air temperature, accurate values of temperature in the rooms of residential areas are difficult to estimate by the current satellite-supported observation. It is thus meaningful to conduct accurate measurements of air temperature within the residential areas, adopting different passive cooling treatments to clarify the optimal application of passive cooling technologies. Applying an empirical approach, the cooling effects would then be more accurately estimated by LST and other measures derived from remote sensing to facilitate the quick and convenient evaluation of the cooling effects.

The most recent residential areas in Bangkok were demonstrated to be significantly cooler than the older ones. Roof cooling treatment on old buildings significantly drops the LST of the area. This suggests that older residential areas have lost their cooling effects. Indeed, it was demonstrated that some of the residential areas completed between 2005 and 2012 lost cooling functions, and the loss was very likely due to roof deterioration. Thus, to maintain passive cooling effects in residential areas, renewal activities are necessary every few years. These findings are meaningful because they aid in the prevention and mitigation of the urban heat island phenomenon.

6- Declarations

6-1- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6-2- Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6-3- Institutional Review Board Statement

Not applicable.

6-4- Informed Consent Statement

Not applicable.

6-5- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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