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Urban heat islands in transit-oriented development designated areas in a high-latitude city - Edmonton, Canada

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Abstract
Transit-oriented developments (TODs), as a smart growth policy, have gained popularity as a way to combat the negative effects of urban sprawl. TODs are also purported to have both environmental and socio-economic benefits. However, little or no research exists regarding their environmental impact, specifically in high-latitude cities. This study aims to bridge the knowledge gap in the literature by analyzing the relationship between TODs and the urban heat island (UHI) effect, which is an environmental phenomenon that results in high temperatures in urban areas. We studied seven transit stations in the city of Edmonton, Canada designated as sites of transition to TODs, to determine the extent of UHI effects in TODs in high-latitude cities. Our results show a significant UHI effect in Edmonton's TOD-designated (TODD) areas over the last decade compared to non-TODD areas. The variation was mainly linked to the reduced vegetation cover at the expense of increasing developments. Although non-TODD areas also experienced an increase in temperature, the rate of increase in land surface temperature (LST) and UHI effect was higher in the select TODD areas. Our findings suggest urban planners should consider UHI mitigation strategies such as preserving or increasing natural landscape as a key requirement to developing and designing the newly built forms in TODD areas.

Keywords: urban heat island; transit-oriented developments; surface temperature, high-latitude city, Edmonton

Résumé
Les aménagements axés sur les transports en commun (TOD), en tant que politique de croissance intelligente, ont gagné en popularité comme moyen de lutter contre les effets négatifs de l'étalement urbain. Ce type d'aménagement sont également censés présenter des avantages à la fois environnementaux et socio-économiques.
Cependant, il existe très peu de recherches sur leur impact environnemental, en particulier dans les villes des hautes latitudes. Cette étude vise à combler le manque de connaissances dans la littérature en analysant la relation entre les

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TOD et l'effet d'îlot de chaleur urbain (UHI), qui est un phénomène environnemental entraînant des températures élevées dans les zones urbaines.
Nous avons étudié sept stations de transport en commun de la ville d'Edmonton (Canada) désignées comme sites de transition vers les TOD, afin de déterminer l'étendue des effets de l'UHI dans les TOD dans les villes de haute latitude. Nos résultats montrent un effet UHI significatif dans les zones désignées TOD (TODD) d'Edmonton au cours de la dernière décennie par rapport aux zones non TODD. La variation était principalement liée à la réduction de la couverture végétale au détriment de l'augmentation des aménagements.
Bien que les zones non TODD aient également connu une augmentation de la température, le taux d'augmentation de la température de la surface des terres (LST) et l'effet UHI étaient plus élevés dans les zones TODD sélectionnées. Nos résultats suggèrent que les urbanistes devraient considérer les stratégies d'atténuation de l'UHI, telles que la préservation ou l'augmentation du paysage naturel, comme une condition essentielle au développement et à la conception des formes nouvellement construites dans les zones TODD.

Mots-clés : îlot de chaleur urbain ; Développements axés sur le transport en commun ; Température de surface, ville des hautes latitudes, Edmonton

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Introduction

By 2050, cities are anticipated to house 60% of the world's population (United Nations 2014). As cities grow, they will continue to expand outward, consuming greenfield areas to make way for impervious surfaces, buildings and other infrastructure and services. This uncontrolled expansion of cities into low-density, car-oriented neighbourhoods comes at the expense of natural areas and agricultural land, given over to the built-up region (Bhat et al. 2017); this trend is exacerbating the urban heat island (UHI) effect.

The UHI effect refers to a phenomenon in which urban and core areas within a city experience higher temperatures compared to their surrounding rural areas (Ward et al. 2016). UHIs occur in almost all cities worldwide and have been shown to have direct relationships with new urban developments (Fischer et al. 2012; Maloley 2010; Mohajerani et al. 2017; Santamouris 2015; Tzavali et al. 2015). As cities expand and new developments arise, they often bring about changes in land use and surface materials such as asphalt and concrete. Several studies conclude that sprawl development is one of the major contributors to the UHI effect in cities (Debbage and Shepherd 2015; Stone and Rodgers 2001) as it leads to increased impervious surfaces, such as roads and buildings (Debbage and Shepherd 2015). More specifically, impervious surfaces such as concrete and asphalt used to construct roads, driveways, parking lots and other structures have lower albedo and higher thermal inertia meaning that they absorb and store more solar radiation and heat up the surrounding area, which in turn leads to urban regions experiencing a higher temperature than their rural surroundings. Previous studies have indicated that UHIs adversely affect the health and well-being of the residents such as increasing heat-related illnesses and deaths (Fischer et al. 2012; Mohajerani et al. 2017; Rinner and Hussain 2011; Sangiorgio et al. 2020; Tzavali et al. 2015).

To combat sprawl's negative impacts on the environment, cities are implementing transit-oriented developments (TODs) as they expand their mass transit system. The concept of TOD was introduced in the late 1980s by Peter Calthorpe (1995) in *The Next American Metropolis* book, proposed as a means to reduce sprawl (Jamme et al. 2019). Calthorpe conceived TODs as sustainable communities around major transit hubs and corridors. Unlike sprawl developments, TODs are described as mixed-use, walkable, dense, environmentally sustainable neighbourhoods within a five- to ten-minute walk[1] of a major transit node (Jamme et al. 2019; Knowles 2012; Wu 2006). In practice, TODs are implemented in many different configurations around transit nodes with a varying mix of uses, population and building density and distance from transit stations (Thomas et al. 2018; Zaina et al. 2016). Furthermore, there is no consensus on what a perfect TOD looks like (Kumar et al. 2020; Singh et al. 2012). However, municipal planning practitioners agree to recognize TODs as a sustainable planning tool (Tong et al. 2018).

Previous studies have indicated a significant increase in UHIs in high-latitude cities[2] (Venter et al. 2020; Welegedara et al. 2023). While much of the existing literature has focused on the UHI effect of urban sprawl and the built form, the current literature does not give a clear picture of the influence of UHI intensities in TOD areas

(Kamruzzaman et al. 2018), particularly in high-latitude cities. To fill this gap, we conducted this study selecting Edmonton because of its high-latitude location (located between 53 and 54 parallels) and rapid increase of built-up areas in the past 20 years (Agrawal 2016; Wang 2018), which may contribute to the UHI effect in the city.

Kamruzzman et al (2018)'s study is arguably the only one—conducted in the tropical city of Brisbane, Australia—that explores the relationship between UHIs and TODs. This study concluded that TODs in Brisbane experienced a higher UHI effect compared to non-TOD areas of the city. No studies take up this concern in a high-latitude city. Thus, Edmonton is ideal for our research: it is not only North America's northernmost major city, but it is also moving towards developing compact and dense developments around transit nodes and corridors along its expanding light rail system (City of Edmonton 2020). Given the popularity of TODs in Canada and elsewhere, municipal planners and policymakers must have a better understanding of the relationship between UHIs and TODs if they wish to promote the development of healthy and sustainable cities. It is equally important for them to be aware of the current levels of UHIs in the areas currently designated for future TODs and in transition to becoming TODs and craft policies so that the UHI effects can be mitigated in future TODs.

Of note, because of the lack of consensus about the precise parameters such as density, land use, or building and site design for a TOD, it is challenging to assess whether any area around transit stations in Edmonton is indeed a true TOD. Our preliminary examination shows that the current net residential dwelling density within the areas does not meet the minimum density targets (42 dwelling units per hectare) proposed by the City for the selected stations, meaning that these areas are not fully developed as TODs. This is another reason for our focus on the City of Edmonton's designated TOD areas around select transit stations of the light rail system; these designated areas will be developed as full TODs in the future.

The main objective of this research is to understand if UHIs exist in TOD-designated (TODD) areas and, if so, how that can potentially be minimized in the future development of these areas. To fulfill this objective, this study will answer the following three research questions:

- Do TODD areas around transit stations in a winter city such as Edmonton currently experience the UHI effect? If so, what factors contribute to the UHI effect in these areas?
- Did the UHI intensity in TODD areas change temporally?
- What can be done to minimize UHI effects in the future development of TODD areas?

Literature review

UHI refers to an island of warmer temperature within an urban area when compared to its surrounding suburban and rural areas (Oke 1982; Stewart and Oke 2012; Santamouris 2015; Ward et al. 2016). Previous studies have demonstrated that UHIs lead to an increase in local temperatures by increasing energy demand, as well as contribute to heat-related mortality (Deilami and Kamruzzaman 2017). Further, much of the existing literature shows that urban sprawl has added to the intensification of heat islands by replacing vegetation with built areas (Debbage and Shepherd, 2015; Deilami and Kamruzzaman, 2017; Lemonsu et al. 2015; Stone and Rodgers 2001). This UHI increase is linked with the replacement of natural permeable green and blue landscapes with impermeable, non-evaporating, built-up areas with high thermal inertia, such as roadways, buildings, and other urban structures and surfaces that absorb and store shortwave solar radiation (low albedo), and re-emit longwave radiation (high emissivity) (EPA 2020; Santamouris 2015).

Urban sprawl also results in land-use and land-cover changes, which collectively play a significant role in intensifying, but alternately reducing, the UHI effect (Yue et al. 2019). In other words, impervious surfaces amplify the UHI effect while vegetation and water-covered areas minimize the UHI effect (Ogashawara and Bastos 2012; Yue et al. 2019). More specifically, Tan et al. (2021) indicated that an additional 10% of green space cover can diminish the average Land Surface Temperature (LST) by 0.39°C.

As previously mentioned, only a handful of studies assess the UHI effect of a particular type of development, such as TODs. A study by Yue et al. (2019) noted a lower UHI effect in neighbourhoods with smaller built-up areas compared to those with larger built-up areas. It concluded that urban configuration and urban characteristics can explain 41% of the variances in UHIs during summer days. Clearly, urban configuration and design are important in mitigating or amplifying the UHI effect.

The Brisbane study, mentioned before, argues that TOD neighbourhoods experienced a higher UHI effect level than non-TOD neighbourhoods (Kamruzzaman et al. 2018). The results of this study are antithetical to the conventional planning knowledge about transit-oriented developments and need further investigation to see if its results hold true in other parts of the world. In response to this gap, our research is unique in its exploration of the UHI effect of TODs and the factors contributing to the UHI effect.

Study area

Edmonton is North America's northernmost major city; it is the capital of the province of Alberta and is bifurcated by the North Saskatchewan River. Edmonton has a population of more than one million people (Statistics Canada 2021), and is expected to reach a population of two million by 2040 (City of Edmonton 2020). It has been one of the fastest-growing cities in Canada, with this growth resulting in significant land-use changes in the form of new neighbourhoods, housing, and infrastructure such as mass transit systems (Agrawal 2016).

Edmonton's Light Rail Transit (LRT) system, established in 1962, has grown to include two commercial rail lines (see Figure 1). Our focus is the Capital Line (shown in red in Figure 1), which connects the northeast of Edmonton to the south of the city, and covers a stretch of 21 km and 15 stations in total. The Capital Line will ultimately develop further south, running through suburban neighbourhoods, and stopping just shy of Anthony Henday Drive, Edmonton's major highway that circles around the city. The more recent Metro Line (shown in blue in Figure 1) shares the same track as those of the Capital Line, eventually separating in the northwestern part of the city. The new Valley Line Southeast opened in November 2023 and stretches 13 km from downtown Edmonton to the southeast, with 11 street-level stops. However, we have not used these stations as they were not built at the time of conducting this study.

In this research, we selected seven of the city-identified transit-oriented developments from among the Capital Line's eight above-ground stations, which are yet to take shape as full-fledged TODs. This choice was based on the definition of TOD encapsulated in the City of Edmonton's Transit-Oriented Development Guidelines (City of Edmonton 2012). The City's guidelines define TODs as high-intensity, mixed developments within a 400m radius of LRT stations and transit centres (City of Edmonton 2012). Edmonton expects between 42 and 225 dwelling units per hectare depending on the size of the lot, location—inner city, urban or suburban—station, and how far it is from the station i.e. within 200m or 400m of the station. The City also proposes certain employment and retail land use intensity based on distance from and location of the station in the city.

It is important to note that the nature and configuration of current developments around the LRT stations are vastly different and are at various stages of development, which will continue as time goes on. In this study, we limited ourselves to TODDs, where residential developments are encouraged by the City and are more likely to occur in the future. As mentioned before, our preliminary examination shows that the current net residential dwelling density does not meet the City's minimum threshold for any of the selected stations. The TODD areas will take some time to fully develop as TODs per the City's TOD guidelines, which came into effect only a decade ago.

Following these criteria, we chose to exclude two stations in the University of Alberta's North campus and five deep underground stations in the downtown area, since their surrounding built forms are office towers or institutional buildings, which existed prior to 2012 when the TOD guidelines came into effect, have remained largely unaltered since then and will continue to remain so in the foreseeable future. The South Campus LRT station was also excluded from the study area because it is surrounded by large green spaces and disparate institutional buildings. The current use is likely to remain the same in the coming years. The stations are described below, ordered according to their sequence on the rail line from South to North, are surface stations and the areas around them have tremendous potential for new developments:

- *Century Park* is at the south end of the rail line and is characterized by a mix of low to mid-rise commercial as well as single-family and new multi-family residential land use. A new high-density residential building has just been completed in the immediate proximity of the station.
- *Southgate* is surrounded by a large mall, retail developments, parking lots, and other low-intensity use on the west, with low-density residential homes located on the east side.
- *McKernan/Belgravia* is surrounded by predominantly single-detached and mid-rise multi-family homes, with some commercial and institutional development. The McKernan-Belgravia Station Area

Development Plan intends to densify the neighbourhoods in the proximity of the station through midrise and low-rise structures, row housing, and some lower-density infill housing options (City of Edmonton 2022).

- *Stadium* is next to the Commonwealth Stadium, and is a mix of low- and high-density residential developments, as well as commercial and industrial land uses beyond the stadium. The area has an Area Redevelopment Plan which anticipates potential new residential and employment use (City of Edmonton 2018).

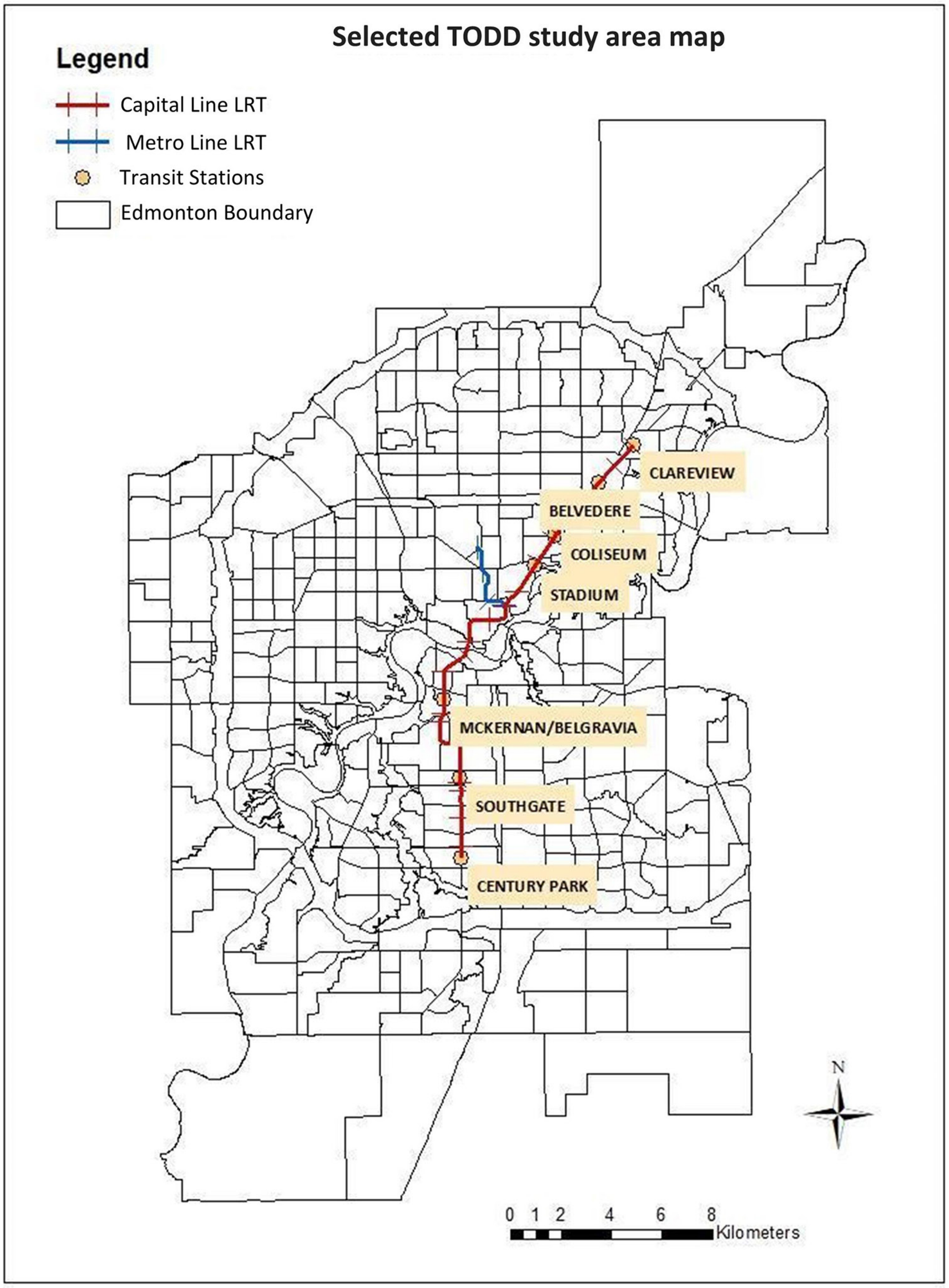

Figure 1
Map of the study area. Highlighted areas represent the selected LRT station and the TOD areas around them on the Capital Line, while the blue path represents the Metro Line. The map was created by authors using ArcGIS® software by Esri and the City of Edmonton's neighbourhood classification map (City of Edmonton 2017).

- *Belvedere* sits amid large parking lots and multiple retail stores in its immediate vicinity and industrial and low-density residential areas in proximity. The Belvedere Station Area Plan anticipates medium to high-density residential and mixed-use development around the station. New condo projects are currently planned for the sites close to the station.
- *Coliseum* is surrounded by commercial and low-density residential uses and the Northlands with a large horse race track and a casino and the Expo Centre.
- *Clareview* is wrapped around by greenspaces, and parking spaces, flanked by multi-family residential buildings and some commercial uses. The Clareview Neighbourhood Area Structure Plan (City of Edmonton 2018) guides the future development residential uses of varying densities and forms in the immediate proximity of the station, wrapped with commercial uses such as neighbourhood com mercial, general business, and shopping centre, and institutional uses such as school campus/park, and recreational facility site.

A few of these stations and adjacent areas, where parking lots are dominant, are frequented by a large number of people who from different parts of the city take the LRT to come for shopping, entertainment, sports or other leisure activities. Of note, the areas in immediate proximity or close to each of these stations are primarily residential or have plans to be developed for residential use in the near future.

Methodology

In Edmonton, there is limited weather station coverage, inhibiting measuring the air temperature of the area under study. In such situations, satellite images are useful to derive SUHIs—a proxy for heat exposure and UHI effects—which exhibit spatial and temporal UHI variations in areas within a city (Hsu et al. 2021; Simwanda et al. 2019; Welegedara et al. 2023). These limited weather data were insufficient to understand long-term temperature variations in the TODD areas. We therefore used SUHIs, retrieved from satellite images, to describe the magnitude and intensity of UHI effects in the TODD and non-TODD areas in the city. Our methodology consisted of four major steps as shown in Figure 2. They are: 1) downloading satellite data using Google Earth Engine (GEE), 2) delineating TODD and non-TODD areas within the city, 3) deriving UHI from LST, Normalized Difference Vegetation Index (NDVI), and Fractional Vegetation Cover (FVC) values for the TODD and non-TODD area, 4) conducting statistical analysis to understand the extent that TODDs contribute to the UHI phenomenon and to identify the effect of NDVI, FVC, and the built-up area in intensifying the UHI effect.

Downloading satellite data from GEE

The United States Geological Survey (USGS) provides Landsat surface reflectance (SR) and top of atmosphere (TOA) data, which are publicly available for Landsat 4-8 satellites. We used Landsat 5 TM (Thematic Mapper) images for the years 2010 and 2011 and Landsat 8 OLI/TIRS (operational land imagery/thermal infrared sensor) images for the years 2014, 2018, and 2020 to derive land surface temperature (LST) and other indexes such as NDVI and FVI for the Edmonton area (Table 1).

We used the GEE code developed by Ermida et al. (2020) to derive LST maps. Statistical Mono-Window (SMW) algorithm (Equation 1) developed by the Climate Monitoring Satellite Application Facility was used to derive LST maps from thermal bands and the complete processing chain used to derive LST maps can be found in Ermida et al. (2020).

$$LST = A_i + \frac{Tb}{\varepsilon} + B_i \frac{1}{\varepsilon} + C_i \quad \text{(Equation 1)}$$

Where: T_b is the TOA brightness temperature in the TIR channel, ε is the surface emissivity, and A_i, B_i and C_i are the algorithm coefficients. These coefficients were derived from linear regression of radiative transfer simulations (Ermida et al. 2020).

UHI effect is higher during the summer compared to other seasons. Therefore, we used cloud-free images that were acquired during summer (from July 25 – August 16) for our analysis. Table 1 describes the wavelengths, spatial resolution, and acquisition dates of the thermal images that were used to derive LST maps.

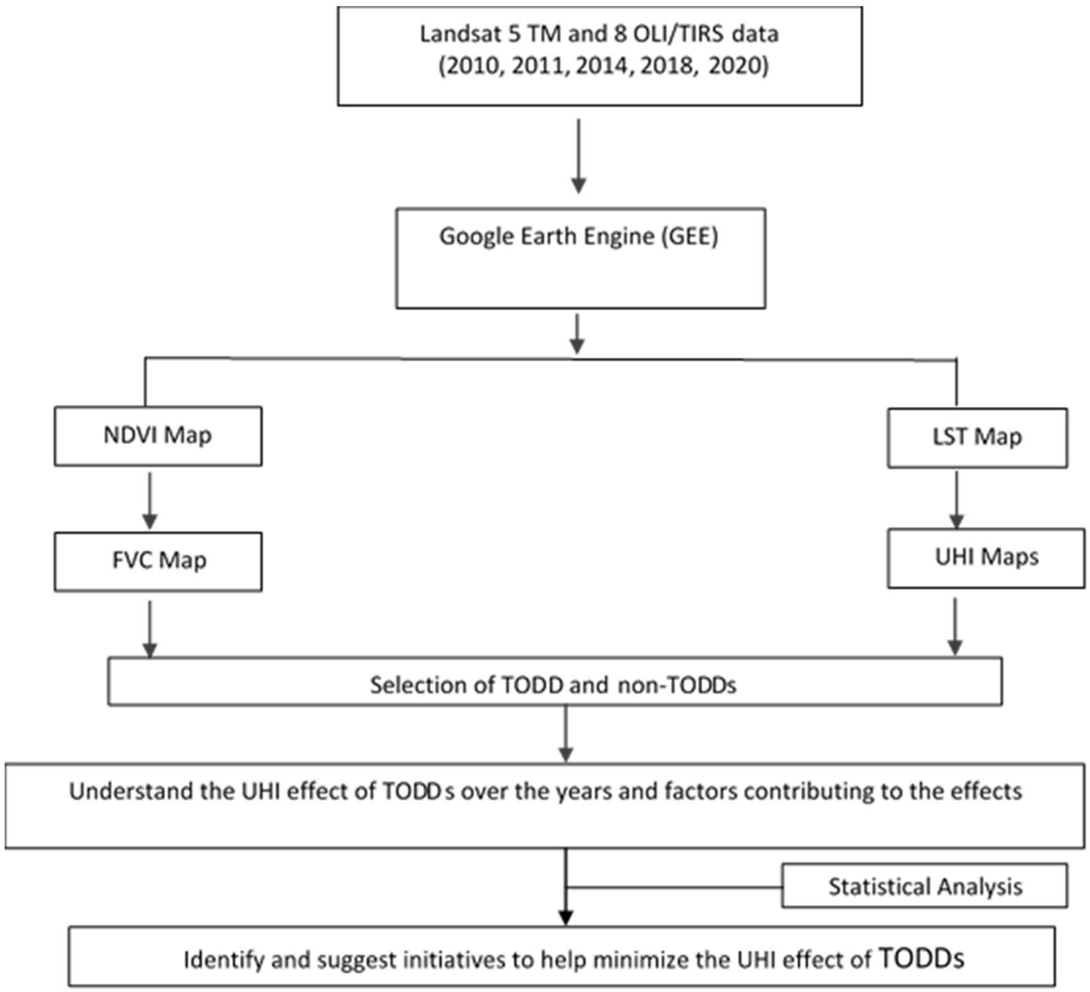

Figure 2
Schematic diagram of the research methodology

Table 1
Satellite imagery details

Satellite type	Band number; Wavelength (μm)	Spatial resolution	Acquisition date
Landsat 5 TM TIR	Band 6 (10.40–12.50)	120 (30)*	July 31, 2010 August 7, 2010 July 25, 2011 August 10, 2011
Landsat 8 OLI	Red, Band 4 (0.636-0.673) Near infrared, Band 5 (0.851-0.879)	(30 m) (30 m)	August 2, 2020 August 18, 2020
TIRS	Band 10 (10.60–11.19)	100 (30)*	August 2, 2014 August 11, 2014 July 28, 2018 August 6, 2018 August 2, 2020 August 18, 2020

**resampled to 30m*

Note that the resampling of thermal images from 120 m to 30 m using the cubic convolution method (Bonafoni et al., 2016; USGS, 2023) enhances the image quality, but does not enhance the scale variability to show objects such as buildings, houses, roads, driveways and yards and not representative of the land cover at 30 m. In this study, we calculated the average LST and UHI changes for the TODD and non-TODD areas. Therefore the pixels in the areas represent the average temperature changes of all the objects within the area. We have used Landsat Level 2, Collection 2 Tier 1 thermal data for this study as that is the highest spatial resolution scientific data available for long-term studies.

Deriving UHI Maps

To create UHI maps for Edmonton, we considered the difference between urban and rural temperatures (Equation 2). To calculate the rural temperature, we determined the built-up area within the city and extended this analysis to cover a 10-kilometre distance outward from the established city boundary. The choice of a 10-kilometre buffer was deliberate, as it corresponds to half the width of the city boundary and ensures a precise assessment of rural Land Surface Temperature (LST), as previously established by Zhou et al. in 2015.

$$UHI = LST_u - LST_r \quad \text{(Equation 2)}$$

Where: LST_u is the land surface temperature of the urban area and LST_r represents the land surface temperature in the rural area.

Identifying TODD and non-TODD areas

As previously noted, we chose developments around seven above-ground stations of the Capital Line. Following other scholars (Du et al. 2008; Zhou et al. 2015), we used a zonal analysis for this study. As per the definition of TOD under the City of Edmonton guidelines (City of Edmonton 2012), we created an area of a 400m radius around each station and classified it as the TOD area. We designated the non-TODD area as the 200m buffer from the 400 m radius to the 600 m radius, thereby adding an additional 200 m to the full radius zones we considered. For comparative analyses, this 200 m buffer surrounding the identified TODD area was the best choice to be designated the non-TODD area because of its similar geographical positioning, and microclimate. Selecting a non-TODD buffer farther away from the station would have skewed our results. We then compared the LST and UHIs for each paired TODD and non-TODD over the years. A sample of the buffers is illustrated in Figure 3.

Deriving NDVI and FVC for non-TODD and TODDs

In the sections that follow, we provide relevant details about calculating NDVI and FVC, as well as an overview of the statistical analysis we performed for the study.

Normalized Difference Vegetation Index. NDVI is widely used s to quantify vegetation coverage, and understand plant health. NDVI is calculated using red and near-infrared bands as indicated in equation 3. This depends on the spectral signature of the vegetation cover, where typically healthy vegetation strongly reflects near-infrared and absorbs red light. When vegetation is unhealthy, sparse, and consists of grassland or bare soil, more near-infrared is absorbed and reflects more red, having little difference between values. NDVI values range from -1 to +1, where a value close to +1 indicates the dense green vegetation, closer to -1 is generally shown by the water bodies, and areas with no vegetation indicate a value closer to zero (Pettorelli et al. 2005). We used the ERDAS IMAGINE software to derive NDVI maps using Equation 3.

$$NDVI = \frac{Near\ Infared - Red}{Near\ Infared + Red} \quad \text{(Equation 3)}$$

Where: NDVI is the Normalized Vegetation Index. Near-infrared represents the reflection in the near-infrared spectrum while Red is the reflection in the red spectrum.

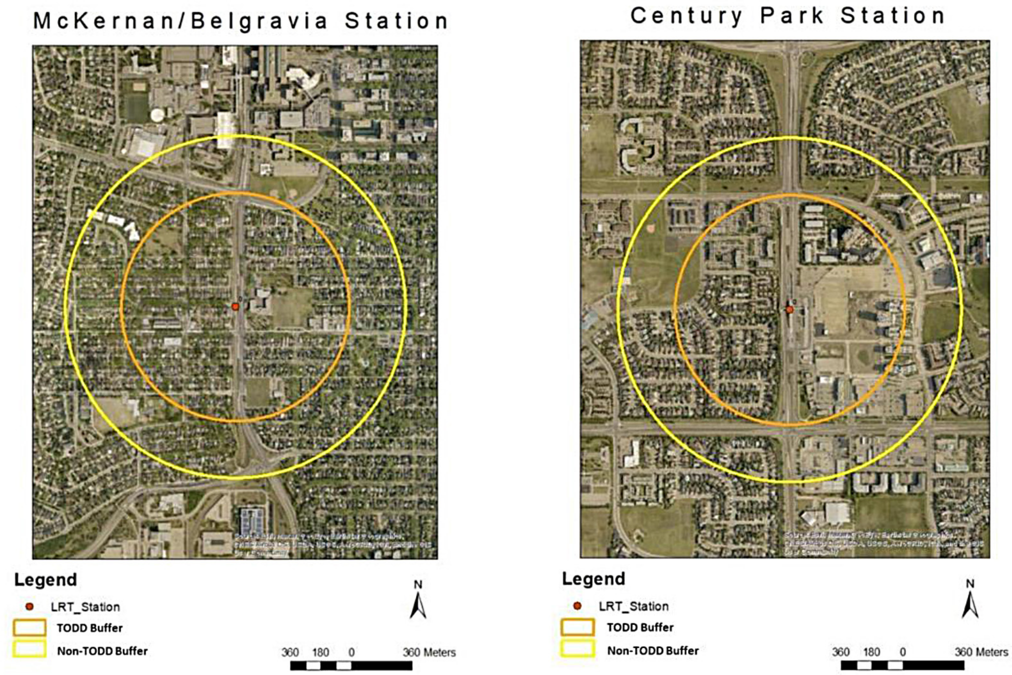

Figure 3
Detailed map of the TODD and non-TODD buffer (created by authors using ArcGIS® software by Esri)

Fractional vegetation cover. Previous studies have identified that FVC had a stronger effect on LST compared to NDVI (Zhao et al. 2020). NDVI considers vegetation, water bodies, and open areas when calculating the index (Gandhi et al. 2015), whereas FVC only corresponds to the density of vegetation. As a result, we used NDVI to estimate FVC, which has proven to be a better indicator of plant growth and the distribution of the density of vegetation (Liu et al. 2019; Ermida et al. 2020).

$$FVC = \frac{(NDVI - NDVI_{bare})}{(NDVI_{veg} - NDVI_{bare})} \quad \text{(Equation 4)}$$

Where: FVC is the fraction of vegetation cover, NDVIbare represents the bare land pixels (NDVI = 0.2), and NDVIveg represents the fully vegetated pixels (NDVI =0.86).

Data Extraction and Statistical Analysis

We extracted the average LST and UHI for each TODD and non-TODD area and obtained the area covered by vegetation and built surfaces. We used a paired t-test to determine the difference in UHI intensity in both TODD and non-TODDs from 2010 to 2020. Additionally, we used a Pearson's correlation analysis to quantify the relationship between UHI intensity and the fraction of vegetation cover (n= 28) in 2020. All the statistical analyses were performed using SPSS.

Results and discussion

This section discusses our findings on the average LST and UHI changes in Edmonton's TODD and non-TODD areas, the potential effect of future Transit-Oriented Developments on the UHI intensity, and the other associated factors that influence the UHI effect.

Average LST and UHI changes in TODD areas

The average LST (°C) values for all the TODDs (n=7) have considerably increased over the last decade. In 2010, the mean LST for the seven TODD locations was 32.31°C, while in 2020, the mean LST for these areas was 39.47°C. Over ten years, the average land surface temperature in TODDs thus climbed by 7.16°C.

In addition, LST increased in each station over the 10-year period, though the increase significantly varied among the stations (Figure 4). Century Park, Southgate, Stadium, Clareview, and Belvedere TODDs have comparable LST trends through time. However, due to their built environments—unlike the five other stations—the McKernan/Belgravia station showed significantly lower UHIs and the Coliseum station, had markedly higher UHIs. We observed the lower LST and UHI values, consistent across the time period, compared to the average UHI and LST values of other TODDs for the McKernan/Belgravia TODD station. On a summer day in August 2020, the LST and UHI for McKernan/Belgravia TODD were reported as 36.44°C and 5.68°C, respectively. On the same day, the Coliseum station reported the highest LST and UHI intensity of 41.59°C and 10.83°C, respectively. The LST difference of 5.15°C between the two stations, was substantial within one city. This variation in temperature may be related to not only TODDs' distinctive land-use patterns, but also the effects of surrounding areas. For instance, McKernan/Belgravia has a much higher vegetation cover with mature trees/treelines, and the ravine system while Coliseum is dominated by a horse race track, a casino and associated parking lots.

As mentioned before, large asphalt and concrete surfaces absorb shortwave solar radiation (low albedo) and re-emit the longwave radiation (high emissivity) more than natural green and blue landscapes do (EPA 2020; Imhoff et al. 2010; Klock et al. 2012; Mohajerani et al. 2017; Santamouris et al. 2011; Tzavali et al. 2015; Unger, 2004), which leads to higher surface and air temperatures. Our findings are consistent with previous research and highlight the role of land covers in amplifying or weakening the UHI effect (Gupta et al. 2019; Zhou et al. 2011).

Effect of TODDs on the UHI intensity

Our results show an increase in the UHI intensity in the selected TODDs (n=7) over the last decade. Table 2 shows the variations of UHIs in TODD vs non-TODD areas in 2010, 2011, 2014, 2018, and 2020. Although some variation occurs over time, an overall upward trend in the UHI effect is noticeable. The lower UHI intensities in some years (particularly 2014 and 2018) can be attributed to boreal wildfires (David et al. 2018) in northern Alberta,

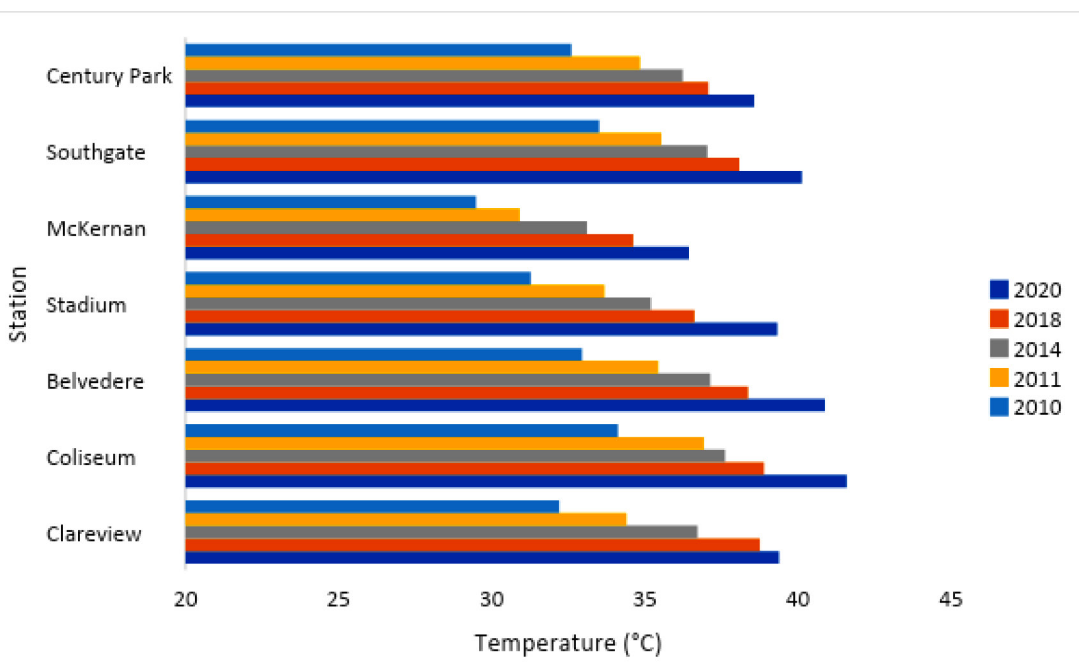

Figure 4
Average LST changes over the past 10 years

which caused a cooling effect in Edmonton. This is mainly because the smoke from the wildfire reduced the amount of incoming solar radiation due to the presence of aerosols, resulting in daytime cooling (Kochanski et al., 2019; Robock 1988, 1991).

Further, our findings indicate that the magnitude and rate of UHI increase were higher in TODD areas compared to non-TODD areas. Between 2010 and 2020, the UHI effect increased by 0.94°C within TODDs and by 0.86°C within non-TODD areas. The UHI effect of TODDs, on the other hand, was significantly greater ($p<0.001$) when compared to the adjacent non-TODD areas, largely due to the lower levels of vegetation and water bodies in and around the TODDs. Our findings are therefore consistent with the Brisbane study (Kamruzzaman et al. 2018).

Factors contributing to the UHI effect

Differences in the LST and UHI in cities are caused primarily by impermeable, non-evaporating urban structures and surfaces that pave over natural, permeable green spaces. As discussed before, these surfaces tend to absorb and store solar heat, increasing surface temperature. It subsequently causes a rise in surrounding air temperature when the heat is released (EPA 2020; Santamouris 2015). To further understand this phenomenon in the context of Edmonton, we conducted a correlation analysis for both TODDs and non-TODDs to examine the relationship between UHIs and FVC. Results show a strong negative relationship between the FVC and the UHIs ($r= -0.9$; $p<0.001$). This demonstrates that FVC greatly contributes to reducing the UHI effect in TODD areas.

The results indicate that the TODD areas' land use/land cover can significantly influence the LST and UHI effect. Areas with vegetation, particularly trees, had a greater influence on reducing the UHI effect in the area by providing shade and reflecting more solar radiation and through the process of evapotranspiration. Furthermore, the presence of water bodies contributed to minimizing the UHI effect as they tend to change wind patterns and cool the area (Coseo and Larsen 2014; EPA 2020; Tan et al. 2021). This scenario was clearly observed in McKernan/Belgravia station which is located near the North Saskatchewan River and the surrounding river valley area. These findings are consistent with those reported by other studies arguing that the main contributor to the UHI effect is the reduction of vegetation cover due to urbanization, which leads to less evapotranspiration (Chapman et al. 2018; Chun and Guldmann 2014; Tran et al. 2017).

Another potential factor for the increase of UHI in Edmonton's TODD areas can be the increase in air temperature as an impact of climate change. However, if climate change is a main player, it would impact both TODD and non-TODD areas equally. The results of this research show that the rate of increase in the UHI in TODDs was higher than in non-TODD areas surrounding them, suggesting that some other mechanism is in play (e.g. the variables included), otherwise, the rate of increase should be similar in all type of areas. Also, TODDs experienced a higher UHI intensity in multiple years between 2010 and 2020 compared to non-TODD areas suggesting that designated TODs are historically high temperature zones in the city.

We argue that simply increasing building density or mixed use around transit stations alone will not help achieve sustainable development from the environmental aspect. Rather, future TODs need to be developed in a climate-friendly way from the beginning, with respect to the local environment and open spaces. Our research recommends that the most simple and effective way to mitigate the UHI effect is through implementing green infrastructure to co-exist with built-up areas, which consists of preserving mature trees, planting more trees and native species along streets, vertical gardening, living green walls and increasing the amount of vegetation within TODDs development concepts. The current TOD policy developed by the City of Edmonton (City of Edmonton 2012) falls short: It lacks specifics on environmental features such as street trees and other forms of vegetation and any adverse impacts of future development.

How to avoid UHI intensities in TODDs?

The current City of Edmonton TOD Guidelines (City of Edmonton 2012) have specific requirements for density, bicycle facilities, public realm, and building design. While the guidelines encourage the implementation of urban parks, which can certainly be an important factor in mitigating the UHI effect, they are insufficient in requiring a minimum amount of park spaces and are largely silent on many other factors such as building and surface material. We recommend that permeable pavers be required for parking surfaces. High-rise residential and commercial developments of a certain minimum floor area and available roof space could accommodate green roofs. More is needed—in particular, we recommend that new policies and guidelines require TODDs to allocate a specific area for parks, green space, and water bodies. Furthermore, new policies for developing or redeveloping transit nodes, corridors, station area plans, and TODDs should closely align with the City Plan's overall goal to support and preserve the natural environment.

Conclusions

The relationship between TODs and UHI intensity has been largely unexplored. To fill this knowledge gap, we conducted this study to understand how this relationship operates in the winter city of Edmonton by looking at its TODD areas. Results of our study show that TODDs in Edmonton currently experience higher LST and UHI intensities compared to their surrounding non-TODD area. Furthermore, we observed that temporally, the UHI intensity in these TODDs, which are in various stages of development, increased at a higher and faster rate than in non-TODD areas, similar to what Kamruzzaman et al. (2018) observed in Brisbane. Our research indicates that increases in the LST and UHI intensity were closely related to more built-up areas and impermeable surfaces and corresponding decreased vegetation around the selected stations. Clearly, urban configuration and land cover play an important role in mitigating or amplifying the UHI effect.

Our findings have significant implications for the field of urban planning but more specifically for the City of Edmonton as they are aiming to develop their TODD areas at higher density and mixed-use in the future. Through our study, we noticed that the current state of these areas is contributing to the UHI effect. To address this issue, new TODD developments in the identified areas should apply effective heat mitigation measures. Preserving and planting more trees along streets and in parking lots, using green and/or cool roofs and cool materials, and integrating water bodies in the design of TODDs are all strategies that will help ensure that the UHI effect is mitigated in future TODs.

This research has a couple of limitations. First, our study involved only one city, one with a small number of transit stations, which are still being developed as TODs. Future studies should analyze the UHI effect and TOD relationship in different cities of Canada drawing on a larger sample of TODs, which are fully developed as per their respective city guidelines. Second, our study did not include certain variables, such as population and building densities and mobility characteristics, which can contribute to the UHI effect as well as GHG emissions. Future studies could include these and other contributing factors known to affect the UHI effect, such as the building materials used in TODs.

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