Compact and green urban development—towards a framework to assess urban development for a high-density metropolis

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Abstract

This paper proposes a framework for measuring compactness and urban green accessibility in a high-density transit-oriented metropolis and uses Taipei City and its surrounding outskirts, New Taipei City, as a case to illustrate the measurement framework. Two indices, urban compactness index (UCI) and urban green accessibility index (UGAI), are developed to illustrate various aspects of a sustainable urban built environment, with UCI including density of residents and commercial activities, land use mix, street connectivity, access to center/subcenters, and access to transit stops, and UGAI measuring access to public urban green spaces. We found that while great spatial variations exist among different parts, our study area has a distinguished polycentric pattern of UCI index with three distinct clusters around the center and sub-centers illustrating higher index values in 2015. When compared to UCI, UGAI has a similar polycentric but more dispersed spatial pattern, as well as linear patterns along river corridors. We found that most areas of medium or high UCI values are located in areas of either plan-induced or plan-expanded development. UCI values in areas of plan-expanded development are generally higher than that of areas of plan-induced development. UCI and UGAI are spatially correlated to a certain extent. We found that most centers and one particular subcenter have high UCI and UGAI, moving towards both compactness and good green accessibility. Two subcenters with high UCI and low UGAI, i.e. Banqiao and Yonghe, call for planning to provide green spaces for residents living in these rising subcenters. UCI and UGAI can be applied and used to assess compact and green urban development of other cities and they are particularly useful to dense urban environment of large cities in Europe and Asia.

1. Introduction

Urbanization has been addressed as one of the most serious development challenges in the 21st century by the United Nations as more than half of the world population now live in cities. While cities worldwide have manifested a diverse range of spatial patterns, from the typical suburban sprawl to densely developed urban core or new towns at the urban fringes, compact and green urban development has gradually gained attraction in recent years and considered as one of the most viable solutions to this development challenge (Artmann et al 2019). This paper defines a compact and green urban development as a dense, mixed, connected, (poly)centered, transit accessible, and green urban spatial pattern, i.e. it has high-density, characterized by mixed land use urban form, has high street connectivity, easily accessible to center/subcenters, transit stops, and a good access to public urban green spaces. It proposes a framework and a method to measure and compare the compactness and urban green accessibility.
This paper uses a high-density Asian metropolis, Taipei (figure 1), as a case to illustrate the measurement framework. A comprehensive index, urban compact index (UCI) is developed to integrate five aspects of compact urban development in the context of high-density metropolises, including density of residents and commercial activities, land use mix, street connectivity, access to center/subcenters, and access to transit stops. In addition, an urban green accessibility index is created to evaluate the access to public urban green spaces. Using the outcomes of our assessment, we further compare UCI with the land use planning maps of Taipei and discussed major factors contributed to planned or un-planned led compact urban development in Taipei. We also analyze the spatial distribution of and relationships of these two indices. Our framework can be applied and used to assess compact and green urban development of other cities and it is particularly useful to dense urban environment of large cities in Europe and Asia.

2. Existing research and measuring compactness and urban green accessibility

2.1. Literature on compact urban development

Due to the agglomeration effect of human settlements, compact urban development can lead to a suite of benefits, including cost saving, energy saving, and the improvement of environmental quality, social equity, and health. For example, compact cities have been widely recognized by its impact of reducing greenhouse gas emission (Ishii et al 2010, Liu and Sweeney 2012, Ye et al 2015). Compact cities have also been found to have better urban environmental quality such as having less air pollution (Martins 2012, McCarty and Kaza 2015, Rodriguez et al 2016), causing much less annual average temperature increase (Martins 2012), and being less associated with extreme heat events (Stone et al 2010) than cities not in compact forms. Nevertheless, it should be noted that there are significant trade-offs between traffic-based emissions and exposure resulting from urban form, because while sprawl can increase emissions, compactness can increase exposure (Schindler and Caruso 2014). Moreover, compact cities have been found to promote health (Griffin et al 2013, Ewing et al 2014, Garrido-Cumbera et al 2018), advance social equity (Burton 2003), and facilitate society’s upward mobility (Ewing et al 2016) and certain type of social capital (Nguyen 2010). As urban areas are characterized by both concentration of built environment and population, cities have been compact in nature until the wave of suburbanization in the US starting in the middle of the 20th century, followed by the subsequent frenzy of urban sprawl and low density development worldwide. However, with the arrival of the new millennium, we have witnessed a renewed interest in compact urban development globally (Levy 2016).

2.2. Literature on urban green space

Provision of urban green space for its residents has been considered as one of the essential criteria for quality of city life ever since the start of the urban planning in Western Europe and the US. For example, public park movement in the late 19th century not only created the legendary Central Park in New York City but also initiated the design and development of many urban parks across the continent by Frederick Law Olmsted and his design firm. Urban green space has also been used as a city’s image building tool, being considered as ‘green capital’ of the urban amenity to attract companies and residents, especially those of the creative class (Florida 2005). Numerous research have focused on various aspects of urban green space, such as the normative framework of spatial distribution of parks (Tallen 2010), benefits of urban parks (Maroko et al 2009, Reyes et al 2014), and accessibility of urban green space (e.g. Boon et al 2009, La Rosa 2014, Reyes et al 2016).
et al 2014). While urban green space per capita has been considered as a crucial indicator to measure a city’s environment quality and livability (Fan et al 2017), accessibility to urban green spaces has attracted more research as proximity and equitable spatial distribution are considered two important components of a normative framework for spatial distribution of urban parks (Tallen 2010). Review of Maroko et al (2009) highlighted that three main approaches are used to evaluate the accessibility to urban parks. They are: (1) container approach which measures accessibility by the quantity of the area of the parks located within a particular geographic area, (2) walkability distance approach which measures accessibility by distance to parks, and (3) Kernel density estimation approach which measures the accessibility of a reference location by summarizing the values of the distances from all points of the study area to that reference location. In evaluating accessibility, it is also important to incorporate the quality of a green space and evaluate green space at multiple functional levels (from neighborhood, district, to city level) (Van Herzele and Wiedemann 2003, Fan et al 2017). In this research, we decided to use walking distance approach to evaluate the accessibility to urban parks due to the simple calculation of this approach comparing to other two main approaches. In addition, distance to green space is considered more important than quality of a green space when accessing a green space (Fan et al 2017).

2.3. Knowledge gap of researches on compact and green urban development

A combination of compact and green urban development has neither been an easy path, nor a uniform process. Worldwide experiences have shown distinct paths and approaches under different socio-economic, historic, and demographic contexts. In the US continent, compact and green urban development began to resurge during the waves of downtown redevelopment in large US metropolis in the 1980s, particularly in cities such as New York, Chicago, and Portland. Across the Atlantic Ocean, European cities, never as sprawled as their US counterparts, have maintained a relative high-density compact urban form and a hierarchical system of urban green space (Dieleman et al 1999). Meanwhile, outside the geographic scope of the mainstream literature, high-density Asian metropolis have gradually attracted attention due to their combination of high-density development and quality of life of urban environment, illustrated by cities such as Singapore and Taipei (Huang et al 1998, 2009, Newman 2014). Current literature on compact and urban green development highlighted three main issues. First, it is recognized that both compactness and greenness have to be contextualized in multi-scales of a metropolitan area (Artmann et al 2019), resulting in a combination of different land use density and types of green space, e.g. different types of community and neighborhoods (Perry 2013). Second, the existing literature illustrates one distinct knowledge gap as it based on experiences of most cities in North America or Western Europe, thus lacking a wider global perspective. While certain cities such as New York and Copenhagen may be considered leading in compactness and greenness, Asian cities such as Singapore, Tokyo, Taipei, Shanghai, also present a diverse range of planning and policies for compact and green development. Third, there is a lack of appropriate spatial assessment and monitoring tool to assess the compact and green development, particularly for high-density Asian cities at a reasonable resolution. As indicated by walkability and green space studies of Asian cities (Fan et al 2017, 2018), most relevant studies in English literature examine cities of the US and Europe with the resolution of 1 km, which is not appropriate for highly dense Asian metropolis. Fourth, while there are existing analysis on urban compactness and urban green accessibility, few researches have been dedicated to examine the spatial relationship between them. Some questions remain unaddressed, such as, can high-levels of compactness and green accessibility co-exist in high-density metropolis, if so, where do they tend to appear?

2.4. Measuring compact and green urban development

As two sides of one coin, literature on urban compactness cannot be separated from those of urban sprawl. Despite numerous literature on topics of compact or sprawl urban development, there is lack of consensus on concepts or measurements for either urban compactness or urban sprawl (Ewing 1997, Sierra Club 1998, Glaster et al 2001, Ewing et al 2002, Tsai 2005, Angel et al 2007, Bhatta et al 2010, Mubareka et al 2011, Li et al 2013). In a comprehensive literature review, Bhatta et al 2010 found that various dimensions and associated indicators have been suggested to identify either urban sprawl or compact development. For example, Galaster et al (2001) enlisted eight such dimensions for sprawl, including continuity, concentration, clustering, centrality, unclear, mixed uses, and proximity. Angel et al (2007) suggested a total number of 27 metrics to measure five attributes of urban sprawl, including urban extent, density, suburbanization metrics, continuity and openness, and compactness. Jiang et al (2007) proposed 12 geospatial indices for measuring sprawl. While each of these dimensions or indicators represents a valuable aspect of urban spatial pattern either on sprawl or compactness, many of them can be correlated, data can be difficult to get for all cities for different periods, and some of them are too complex to explain to policy makers or residents. However, most literature would agree on three essential land use
characters of urban sprawl, i.e. low development density, segregated land uses, and lack of significant centers (Ewing et al 2002, 2003). In addition, two transportation characteristics, i.e. street connectivity and transit accessibility, have been identified as essential for urban sprawl (Frumkin et al 2004). For these five characteristics, not only most data are available or can be processed easily, the assessment of each character can also be straightforwardly explained to general audience, including policy makers.

In addition to these five characteristics related to land and transportation, public urban green space has been increasingly recognized as an important dimension for sustainable urban development, with accessibility of urban green space considered essential to ensuring quality of city life (Fan et al 2017, Artmann et al 2019).

We define the measurement of compactness to include the following five components and urban green accessibility as follows:

- Density (D): This component includes both net residential (NRD) and commercial density (CD). NRD is defined as the number of population per 0.01 km² of residential use and CD is defined as the area of commercial activities (commercial and office land uses) per 0.01 km².
- Land use mix (LUM): This is the mixed level of seven land use types: (1) residential, (2) wholesale and retail, (3) service industry (hotel, restaurants, and offices), (4) industrial, (5) institutional (e.g. schools, libraries, kindergartens), (6) green/park area, and (7) water and wetland. LUM of a grid cell (size for 0.01 km²) is calculated with a 500 m radius around the center of the grid cell.
- Street connectivity (SC): This is the number of true intersections (i.e. intersections with three or more legs) per 0.01 km² as an indicator of street connectivity. To calculate the street connectivity of a grid cell, a 500 m radius around its center was drawn to count the number of intersections within it;
- Centrality (CT): This is the distance (unit: m) to the closest city center or sub-center
- Transit Stops (TS): This is the number of bus (BS) and subway/light rail stops (SLS) per 0.01 km², the BS or SLS of a grid cell is calculated with a 500 m radius around its center
- Urban Green Accessibility (UGA): This is the distance (unit: m) from the center of the grid cell to the edge of the closest public urban green space. Here the public urban green space refers to the urban parks and publically accessible green space.

Three subcomponents, i.e. net residential density (NRD), street connectivity (SC), and transit stops (TS), are defined either the same as or adapted from Fan et al (2018). The calculations of the indexes of these components are described in table 1:

These variables are normalized into sub indices (valuing between 0 and 1), as following:

\[
\text{Density Index (DI)} = \frac{1}{2} \text{NRD} + \frac{1}{2} \text{CDI} \quad (1)
\]

\[
\text{NRD Index (NRDI)} = \frac{\text{NRD}}{\text{max (NRD)}} \quad (2)
\]

\[
\text{CD Index (CDI)} = \frac{\text{CD}}{\text{max (CD)}} \quad (3)
\]

\[
\text{SC Index (SCI)} = \frac{\text{SC}}{\text{max (SC)}} \quad (4)
\]

\[
\text{LUM Index (LUMI)} = \frac{\text{LUM}}{\text{max (LUM)}} \quad (5)
\]

where:

\[
\text{Land use mix (LUM)} = (-1) \cdot \ln(b1/A) + (b2/A) \ln(b2/A) + (b3/A) \ln(b3/A)
\]

\[
+ (b4/A) \ln(b4/A) + (b5/A) \ln(b5/A)
\]

\[
+ (b6/A) \ln(b6/A) + (b7/A) \ln(b7/A) / \ln(N),
\]

where A is the total area of land for all seven land uses present in the 500 m radius buffer zone, with b1–b7 the measure areas of land use types for residential (b1); wholesale and retail (b2); service industry (hotel, restaurants, offices) (b3); industrial (b4); institutional (b5); green space (b6); and water and wetland (b7). Here, N = 7, summing the number of different land uses present.

\[
\text{Transit Stop Index (TSI)} = \frac{2}{3} \text{SLSI} + \frac{1}{3} \text{BSI} \quad (7)
\]

Here we put more weight on subway/light rail stops due to its relative importance than bus stops in Taipei; or

\[
\text{Transit Stop Index (TSI)} = \text{BSI} \quad (8)
\]

when subways are absent; here

\[
\text{Subway/Light Rail Stop Index (SLSI)} = \frac{\text{SLS}}{\text{max (SLS)}} \quad (9)
\]

\[
\text{Bus Stop Index (BSI)} = \frac{\text{BS}}{\text{max (BS)}} \quad (10)
\]

\[
\text{Centrality (CTI)} = 1 - \frac{\text{CT}}{\text{max (CT)}} \quad (11)
\]

\[
\text{Urban Compactness Index (UCI)} = \frac{1}{5 \text{DI}} + \frac{1}{5} \text{SCI} + \frac{1}{5} \text{LUMI} + \frac{1}{5} \text{CTI} + \frac{1}{5} \text{TSI} \quad (12)
\]

\[
\text{Urban Green Accessibility Index (UGAI)} = 1 - \ln(\text{UGA + 1}) / \ln(\text{max (UGA + 1)}). \quad (13)
\]

The natural log transformation was applied to UGA for normalizing UGAI because the nearest distance to urban green space (i.e. UGA) is highly skewed and log-normally distributed.
## Table 1. Sub-indexes of urban compactness index (UCI) and urban greenness accessibility index (UGAI).

| Sub index                              | Measurement                              | Minimum value | Maximum value | Formula                              |
|----------------------------------------|------------------------------------------|---------------|---------------|---------------------------------------|
| Net residential density index (NRDI)   | Based on value of net residential density (NRD) | 0             | Maximum value of NRD of all grid cells of all periods | NRD/\text{max}(NRD) |
| Commercial density index (CDI)         | Based on value of net commercial density (CD) | 0             | Maximum value of CD of all grid cells of all periods | CD/\text{max}(CD) |
| Land use mix index (LUMI)              | Based on the value of land use mix (LUM)  | 0             | Maximum value of LUM of all grid cells of all periods | LUM/\text{max}(LUM) |
| Street connectivity index (SCI)        | Based on value of street connectivity (SC) | 0             | Maximum value of SC of all grid cells of all periods | SC/\text{max}(SC) |
| Centrality index (CTI)                 | Based on the value of Centrality (CT)    | 0             | Maximum value of CT of all grid cells of all periods | 1-\left[\frac{\text{CT}}{\text{Max}(\text{CT})}\right] |
| Bus stop index (BSI)                   | Based on the value of bus stop (BS)      | 0             | Maximum value of BS of all grid cells of all periods | BS/\text{max}(BS) |
| Subway/light rail stop index (SLSI)     | Subway/light rail stop index (SLS)       | 0             | Maximum value of SLS of all grid cells of all periods | SLS/\text{max}(SLS) |
| Urban green accessibility index (UGAI)  | Based on the value of UGA                |               | Maximum value of UGA of all grid cells of all periods | 1-\left[\frac{\ln(\text{UGA})}{\ln(\text{Max}(\text{UGA})+1)}\right] |
3. Materials and methods

3.1. Study area
Taipei City, the capital of Taiwan, is located at northern tip of Taiwan Island. The name Taipei has often referred to the Greater Taipei Area that includes not only the core of Taipei city, but also its surrounding New Taipei City and Keelung City, a port city that is northeast to Taipei. As the political, economic and cultural center of Taiwan, the metropolitan area hosted about one third of the population of Taiwan, i.e. 7.03 million people, in 2019 (Directorate-General of Budget, Accounting and Statistics DGBAS 2019). In this paper, we select Taipei City and New Taipei City, an area of 2324.8 km² (Taipei City of 271.8 km², New Taipei City of 2053 km²) and 6.5 million population in 2019, as our study area (figure 1) (Directorate-General of Budget, Accounting and Statistics DGBAS 2019). Unless specified, Taipei in this paper refers to Taipei City and New Taipei City. This area is an attractive region for studying urban compactness for several reasons. First, this region is the most densely populated area in Taiwan due to its host of Taiwan’s major socioeconomic center, Taipei City, and the existence of major public facilities such as North-South expressways, high-speed rail, and metro system. Second, Taipei area can be considered as a ‘mixed urban-rural prototype’ for Taiwan, i.e. a typical urban built up area was built in flood prone areas previously used for agricultural practices (Huang et al 2009, Chang et al 2017). The dynamics of land use and land cover change throughout the west coast of Taiwan are fully expressed in this region. Finally, Taipei has a diverse range of urban neighborhoods. The central business district is typical of modern metropolis, with dotted high‐rise office buildings and dense multi-story buildings with mixed housing and commercial activities. The older district is characterized by traditional urban form with cultural assets such as temples. The diversified urban neighborhood in Taipei makes it an ideal area for studying the compactness of a region transformed from an agricultural to a post‐industrial economy, (Huang et al 2019)

The focus of our study area is roughly corresponding to Taipei Basin. The basin is bisected by the Tamsui River, which is joint by three tributaries: the Keelung River from the northeast, the Xindian Creek from the southeast, and the Dahan Creek from the southwest. The Taipei Basin is enclosed by hills and mountainous not suitable for urban development and resembles a washbasin, and some areas are even below the sea level. The urban areas of Taipei occupy the entire central portion of the Taipei Basin. The surrounding mountainous forests, accounting for approximately 65% of the total area and providing important ecosystem service functions for the Taipei area, have been protected mainly for water resource conservation and the prevention of slope hazard. In order to protect the city from flooding and keep pace with growing demand for built-up lands during the 1990, the government not only constructed levees along the major rivers in Taipei Basin but also engaged in straightening the Keelung River to create more space for urban development (Chang et al 2013).

Taiwan was one of the four ‘Asian Tigers’, i.e. Newly Industrializing Economies that include South Korea, Taiwan, Hong Kong, and Singapore that have experienced rapid economic development and industrialization since the 1960s. Taipei is the key economic growth engine that led Taiwan to create this economic miracle. It had the fifth highest GDP per capita in East Asia, only behind Tokyo, Singapore, Hong Kong, and Osaka in 2013, with main economic pillars including information and communication technology, biotechnology, and financial services. The economy of Taipei has transformed rapidly since the 1970s from a rural economy to an industrialized and commercialized one. Urban planning and local economic development influenced the land use changes in the urban planned districts and resulted in a growing number of people moving to its peri-urban areas. Due to the lack of planning guidance in the non-urban planned zones, land use and land cover change in the peri-urban area of Taipei Basin generally took place in nearby existing urban areas or along major transportation corridor, with the increase of the built-up areas in the peri-urban area of Taipei Metropolitan Area much higher than that of the city center (Huang et al 2009, Chiu et al 2019). A significant amount of agricultural lands in Taipei City and its neighboring towns were converted to built-up areas. New built-up lands in the peri-urban area were strongly correlated with areas with high economic growth during the 1971–1990 period, while new built-up lands after 1990 were located in areas close to the urban centers (Wang et al 2018).

We chose Taipei as a case to illustrate our conceptual framework and methodology due to its characteristics of high-density, diversified urban green space, and its representativeness of other Asian metropolises that have a combination of market and government forces in urban development for industrializing economies in Asia. First, the city of Taipei has a high population density of 9800 person km⁻² in 2018, higher than other global cities in East Asia, such as Tokyo (6300 person km⁻²) or Shanghai (4200 km⁻²). Considering more than 50% of its territory is classified as slope land (with slope greater than 5% or altitude higher than 100 m), the real density in built-up area is even denser. Second, urban green space in Taipei consists of two major types: (1) the green spaces along river corridors and the surrounding hill slope areas and (2) the pocket size neighborhood urban parks distributed within the urban planned areas (figure 2). Third, the current urban form, partly a legacy from the Japanese colonization period, is a hybrid product under the dual forces of the planning of the municipal government and market development (Huang et al 2009, Huang et al 2019).
3.2. Data collection and analysis

We collected population density data of Taipei City and New Taipei City (250 m resolution) from the Global Human Settlement of the European Commission (European Commission 2018), which provide data sources for 1975, 1990, 2000, 2014 at 250 m resolution. Land use maps of Taipei City and New Taipei City are collected to calculate land use mix. The officially published land use map of Year 2015 was obtained from National Land Surveying and Mapping Center of Taiwan’s Ministry of the Interior. The original data has 9 main categories, 41 subcategories, and 103 detailed items. This study reclassified the 41 subcategories of land use data into 8 categories: (1) residential; (2) commercial-wholesale/retail; (3) commercial-service; (4) industrial; (5) institutional and roads/transport facilities; (6) green/park area; (7) water and wetland; and (8) others (e.g. barren land).

For example, the original category of built-up lands was reclassified into the new categories of residential, commercial-wholesale/retail, commercial-service, industrial and institutional. The original category of farmland, forest and recreational land are combined into the new category of green/park area. Street network data of the study area were obtained from Open Street Map (OSM) (OSM 2015) to calculate the design aspect, i.e. intersection/street density.

A centrality map of centers and sub-centers in the study area was generated in order to calculate accessibility to these centers and sub-centers (figure 3). These centers are chosen through identifying metro stations that have: (1) high intensity of human activity and (2) high intensity of land use. We define intensity of human activity by the total number of passengers entering and exiting the metro station in 2017, and classify all stations into three categories:

- H I: >25 million
- H II: 25 million – 20 million
- H III: <20 million

The intensities of land uses were reclassified into two categories based on current landmarks and planning map:

- L I: Main public facilities (city hall, landmarks, bus transit station, etc), major business zones, and business zones within specific districts
- L II: Built-up lands located in residential or business zones, general public facilities, stations

We then combine these two criteria to identify centers and subcenters (table 2). Centers are those having both high intensity of human activity (H I) and high intensity of land use (L I), whereas subcenters are characterized by either H I and L I (medium intensity of human activity (H II) and high intensity of land use (L I)) or H II and L II (high intensity of human activity (H III) and low intensity of land use (L II)). We obtained 5 centers, including (1) the corridor of Ximen–Main Station–Zhongshan (hereafter Ximen–Zhongshan); (2) the area around Taipei City Hall (hereafter City Hall); (3) New Banqiao Station District (hereafter New Banqiao); (4) Jiantan Metro Station (hereafter Jiantan); and (5) the linear area along Fuxing N&S Roads (hereafter Fuxing N&S). We further identified 10 subcenters, including Tamsui, Shipai, Shilin, Wanhua,
Banqiao, Guting, Yonghe, Gongguan, Nanjing-Fuxing area (hereafter Nanjing-Fuxing), and the East Shopping District (hereafter Eastern Shopping) (figure 3).

Data on Mass Rapid Transit (MRT) and bus stops for Taipei and New Taipei were downloaded from the website of Ministry of Transportation and Communications (MTC), (Ministry of Transportation and Communications (MTC) 2018). For calculating UGAI, we extracted the subcategory data of 'urban park and public green space' that is accessible to the public, derived from the original land use maps of Year 2015. Urban planning map of the study area was obtained from the Department of Urban Development of Taipei City Government, and the Department of Urban and Rural Development of New Taipei City. The land use and zoning control for the entire city of Taipei has been implemented by urban planning, i.e. the city has only urban planning areas. New Taipei City has both urban planning areas and non-urban planned areas with the urban expansion in New Taipei City is still continuing. The urban development in New Taipei City can be categorized into three types (Chiu et al 2019): (1) plan-induced development; (2) plan-expanded development; and (3) non-urban planned areas (figure 4). Plan-induced development refers to the area that was developed because of the urban plan (e.g. new town development and infrastructure development) and they are usually located in relatively remote areas. Plan-expanded development refers to the area that was developed before the revision of land use zoning plan for accommodating rapid growth of population density, usually located in an urban-sprawled area.

To rule out unsuitable area for urban development, we also processed the slope areas and river and wetland. As for the criteria of slope area, the Taiwan Slope Area Protection Act defines the slope areas as: (1) elevation > 100 m; or (2) slope > 5%. The digital elevation map with 20 m resolution was obtained from the Department of Land Administration of Taiwan’s Ministry of the interior. The river and wetland data were processed from the land use map provided by National Land Surveying and Mapping Center.

To examine the relationship between UCI and UGAI, we draw a scatter plot of UCI versus UGAI for values at each pixel, and fitted regression line to show their correlation. The large amount of pixels may introduce much noise into the model, we therefore also binned the data by UGAI at every 0.02 interval, and fitted a line according to the median UCI and UGAI. To further examine the spatial patterns, the UCI and UGAI were also spatially aggregated (average

![Figure 3. Centrality map with 5 centers and 10 sub-centers. Source: figure created by the authors.](image)
and standard deviation were computed) for each urban center/sub center (figure 3) based on their areal coverage.

4. Findings

4.1. Urban compactness and urban green indexes of Taipei

The spatial patterns of UCI and UGAI are illustrated in figure 5. While UCI has a very clear, concentrated core with high values of UCI, UGAI shows a much extended pattern of areas with high values of UGAI throughout the study area. Overall, high values of UCI clustered in three areas: (1) the city core area in Taipei city enclosed by the Tamsui River, the Keelung River, and the Xindian Creek, all the way east to the Nangang Station (2) the area in New Taipei city south of Taipei City, enclosed by Tamsui River and Xindian Creek (Banqiao and Yonghe Districts), and (3) the area in New Taipei City west to Taipei City along the Tamsui River and the Dahan Creek (Sanchong and Xinzhuang Districts). This spatial pattern of UCI corresponds to the urban growth pattern identified by Huang et al (2009) and Wang et al (2018), especially the two clusters in New Taipei City. In contrast, high values of UGAI are along the river corridors and some scattered within the entire Taipei Basin with many small pockets outside of the city core area.

We further divided the values of UCI and UGAI into five different ranges, low (<0.2), medium (0.2–0.3, i.e. ≥0.2 but <0.3), high (0.3–0.4, i.e. ≥0.3 but <0.4), very high (0.4–0.5, i.e. >0.4 but <0.5) and extremely high (≥0.5) (table 3). The results illustrate that 30% of the whole study area have medium or higher value of UCI with clear distinction differences of Taipei City and New Taipei City: most of the Taipei City (76%) but a small portion of New Taipei City (24%) has medium or higher values of UCGI, respectively. In fact, most of New Taipei City (76%) had low values of UCGI (0–0.2). However, when absolute areas are compared, New Taipei City had much larger areas having medium and higher values of UCGI than Taipei City has. While 205.94 km² of Taipei city has achieved medium or higher values of UCGI, New Taipei City has an area of 491.9 km² that achieved medium and higher values (table 3). The results of UGAI indicates that the whole study area has 55% with low or medium value, but again, with a clear distinction of Taipei City and New Taipei, as only a small portion (14%) of Taipei City but over 60% of New Taipei City has medium or low value of UGAI (table 3).

4.2. Subcomponents of UCI

When each of the subcomponents of the UCI is examined (figure 6), most subcomponents, such as LUMI, SCI, and CTI, reflect the spatial pattern of UCI. High values of Land Use Mix Index (LUMI) are shown...
in the three main clusters identified by UCI. Values of Street Connectivity Index (SCI) are high for the city core of Taipei City as well as for part of New Taipei city adjacent to Taipei City to the south. Values of Center Index (CI) are well distributed in the whole study area. However, there are some interesting spatial patterns shall be noted for Density Index (DI) and Transit Stop Index (TSI). The highest values of DI are concentrated in in Yonghe District New Taipei City, not in Taipei City. Yonghe District is one of the most densely populated areas in the world, with over 38,000 inhabitants per km², 1.5 times of the Dahan District, the densest district in Taipei City. TSI has a peculiar linear pattern with high values of TSI along major metro and bus lines.

4.3. Urban planning and UCI
Figure 7 shows the results of overlaying the urban planning map with the UCI map. The majority of areas...
with higher UCI value are distributed within the urban planning area in the Taipei Basin. Moreover, the areas in non-urban planning area with higher UCI value tend to be adjacent to the existing urban area, indicating that development seems to occur regardless of planning, especially the area that have close proximity to the existing urban built-up area. It is interesting to note that for urban planning areas within the Taipei Basin, the UCI values are not that high (light pink shaded area). The result of less compact development may be due to their remote locations from urban centers and related to intentions of this type of urban planning for specific purposes, such as new town or infrastructure development. In contrast, the UCI values in Taipei City and in urban planning area of New Taipei City with plan-expanded development type (light-blue shaded area) tend to be higher than plan-induced development type. These areas were already developed before performing urban planning, and the announcement of urban planning is to accommodate rapid growth of population density.

### 4.4. Relationship between UCI and UGAI

Values of UCI and UGAI have been correlated spatially (figure 8). While scatter plot of data at the pixel level did not yield a rigorous model ($R^2 = 0.32$) as expected, when UCI data was binned at every 0.02 interval of the UGAI value, a regression line fitted with a good $R^2$ appeared ($R^2 = 0.71$).

In general, both high values of UCI and UGAI are all concentrated in the Taipei Basin, especially along the Tamsui River and Xindian Creek (figure 9). The centers and subcenters on the west side of Taipei such as Ximen–Zhongshan and New Banqiao (see figure 2) have higher UGAI due to their proximity to river corridor. The UGAI of East Shopping has the highest UGAI among other centers and subcenters in the eastern part of Taipei City such as Nanjing-Fuxing and City Hall. Although Yonghe, the subcenter south of Xindian Creek, has a very high UCI, its UGAI is the lowest among all the centers and subcenters. On the contrary, Shilin subcenter has the highest UGAI, but its UCI is the lowest among other centers and subcenters.

It is interesting to note that all centers except Jian–tang have higher UCI and UGAI than the averages of all 15 center/subcenter (UCI: 0.48, UGAI: 0.50) (table 4). In addition, subcenters such as Banqiao, Yonghe, and Wanhu, have higher than the average UCI, particularly Wanhu having a high UCI of 0.53, second to the highest of Ximen–Zhongshan (0.54). For UGAI, subcenters such as Nanjing-Fuxing, Wanhu, and Shipai, and Shilin have than the average UGAI, particularly Shilin with the highest UGAI of 0.71, distancing all others. Using the average value of UCI/UGAI as a dividing line, we assign ‘high’ (H) of UCI/UGAI to places if they have more than the average value of UCI/UCI and ‘low’ (L) otherwise. Thus, we can further classify the 15 centers/subcenters into four categories, (1) high UCI and high UGAI values, including 4 centers and one subcenter, i.e. Ximen–Zhongshan, New Banqiao, Fuxing N&S, City Hall, and Wanhu; (2) high UCI and low UGAI values, including Banqiao and Yonghe; (3) low UCI and high UGAI values, including Nanjing–Fuxing, Shipai, and Shilin; (4) low UCI and low UGAI values, including Tamsui, Gongguan, Guting, and Eastern Shopping).

### 5. Discussions

#### 5.1. Reflections of UCI and UGAI

UCI and UGAI provide us with an evaluation of spatial distribution of urban compactness that is defined as dense, mixed, connected, (poly)centered, transit accessible, and accessibility to public urban green space. They can be easy tools for planners and policy makers to identify the areas that have extremely high or low values of UCI and UGAI. The values of the sub-

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**Table 3. Distribution of UCI and UGAI in Taipei City, New Taipei City, and the whole study area.**

| Range of UCI | Taipei city | | New Taipei city | | Study area whole | |
|--------------|-------------|------------------|-----------------|-----------------|-------------------|
| Low          | 0–0.2       | 63.89 | 24% | 1544.51 | 76% | 1668.4 | 70% |
| Medium       | 0.2–0.3     | 83.66 | 31% | 299.64 | 15% | 383.3 | 17% |
| High         | 0.3–0.4     | 63.83 | 24% | 111.48 | 5% | 175.31 | 8% |
| Very high    | 0.4–0.5     | 47.25 | 18% | 66.69 | 3% | 113.94 | 5% |
| Extremely high| 0.5–1     | 11.2 | 4% | 14.09 | 1% | 25.29 | 1% |
| Sum          |             | 269.83 | 100% | 2036.41 | 100% | 2306.24 | 100% |

**Table 3. Distribution of UCI and UGAI in Taipei City, New Taipei City, and the whole study area.**

| Range of UGAI | Taipei city | | New Taipei city | | Study area whole | |
|---------------|-------------|------------------|-----------------|-----------------|-------------------|
| Low           | 0–0.2       | 0.79 | 0% | 572.1 | 28% | 572.89 | 25% |
| Medium        | 0.2–0.3     | 38.84 | 14% | 661.58 | 32% | 700.42 | 30% |
| High          | 0.3–0.4     | 80.66 | 30% | 481.45 | 24% | 562.11 | 24% |
| Very high     | 0.4–0.5     | 91.59 | 34% | 236.84 | 12% | 328.43 | 14% |
| Extremely high| 0.5–1       | 57.95 | 21% | 84.44 | 4% | 142.39 | 6% |
| Sum           |             | 269.83 | 100% | 2036.41 | 100% | 2306.24 | 100% |
components allow us to understand the contribution of major factors to the overall assessment of UCI. It should be noted that UCI does not equal to crowdedness, as density is only one of the five sub-indexes to be evaluated with a weight of 1/5. However, we do want to be cautious as areas with extremely high-density may make people feel too crowded. Also, the UCI and UGAI can be used to compare different cities or periods if the global maximum for different cities/
periods for each of the subcomponents will be used to normalize the index values.

It is also interesting to note that the areas with highest values of UCI are actually located in areas of New Taipei City that are right adjacent to the Taipei City, rather than Taipei city itself. This is mainly due to their high values of density index (DI), such as the area of Yonghe and Banqiao. Although urban planning in Taiwan can be dated back to the early 20th century during the Japanese Occupied Period, land use zoning control has not been implemented until the 1980s. Taipei is the first city started to implement its land use zoning control in 1983 in Taiwan and has more strict regulation on zoning control than New Taipei City, resulting the denser urban development at outskirts of Taipei City during 1980–2000 (Huang et al 2009).

It seems that the spatial pattern of UCI has generally corresponded to the urban built-up area, i.e. expanding in low-lying area, in areas close to existing urban built-up area and transportation corridor (Huang et al 2009, Chiu et al 2019). It also follows the urban planned districts in the Taipei Basin quite well, with only very small parts of the area that have significant high values of UCGI in non-planned areas. However, it should be noted that two factors contributed to this match. First, as mentioned in 4.3, the de facto development of the built-up area in originally non-planned area forced the planning agencies to react and rezone the areas as urban planned area, leading to the appearance of a large number of areas as plan-expanded areas. Second, in addition to high-density, mixed used urban development, the particular role of transportation network, especially metro lines, shall also be highlighted that leads to current spatial pattern of UCI. Previous studies illustrated that 10% of lands converted from agricultural to urban built-up land from 1971 to 2006 occurred within buffer zones of transportation networks including provincial highways, expressway interchanges, railway stations, high-speed rail stations, and MRT stations (Huang et al 2009). Furthermore, in recent years, MRT stations have become increasingly important not only for urban built-up land conversion, but also different components of UCI, facilitating particularly density, diversity, and transit access for areas around the MRT stations. Taipei Mass Rapid Transit System, or generally referred as Taipei Metro, serves Taipei City and New Taipei City. Although started as early as 1988, the first line opened 12 years later in 1996. The years after 2009 witnessed a rapid expansion of metro lines and stations. The planning of metro lines system was based on the existed urban development pattern and followed the major transportation corridor and extended from Taipei City to the major residential locations in the New Taipei City. Although the zoning along the metro stations were not revised after the construction of the metro system, the continuous growth of the ridership has intensified urban activities along the major metro stations both in Taipei City and New Taipei City.

Although UGI and UGAI correlate spatially in Taipei Basin, the area with the highest UCI do not
necessarily have high UGAI because the most compact
districts in Taipei are mixed-use commercial areas and
most of the urban neighborhood parks are in the resi-
dential districts. The high UCI areas along the Tamsui
River (e.g. Ximen, Wanhua) were historical districts of
Taipei City and they all have high UGAI areas due to
their proximity to the green space along the river cor-
ridor. Yonghe, the sub-center south of Xindian Creek,
has a high UCI but a very low UGAI because the area
was originally sprawled from Taipei city and lacks of
areas for urban park development. Shihlin, one of the
major residential districts in the northern part of Tai-
pei, is close to Jiantan metro station, but the UCI is not
as high as other sub-centers. Due to its proximity to
the urban park corridor that was converted from the
original railway track, Shihlin sub-center has the high-
est UGAI among all the centers and sub-centers in Tai-
pei. On the contrary, although Gongguan is also a sub-

Figure 8. Relationship between UCI and UGAI. Source: figure created by the authors. The scatter points show the relationship at pixel-
level with a regressing line fitted (blue, \( R^2 = 0.32 \)). The boxplot shows the relationship when UCI values are binned for UGAI at 0.02
intervals with a regression line fitted to median value of each box (orange, \( R^2 = 0.71 \)).

Figure 9. UCI versus UGAI for identified centers/subcenters. Source: figure created by the authors. The value and standard deviation of
UCI and UGAI for each center and sub-center are shown as bars.
center in Taipei, its UGAI is lower than other sub-centers because the area is not adjacent to river and also in lack of urban park.

5.2. Limitation and future research
Our research has unavoidably several limitations that we shall overcome in future. First, we only measured the urban compactness and green accessibility indexes (UCI and UGAI) for the year of 2015, as we do not have full sets of data of early periods for comparison at different time periods. This is mainly because of the lack of data for indices such as transit stops (TS) and street connectivity (SC) for different periods. The single year evaluation made it difficult to evaluate the spatio-temporal change of UCI and UGAI that can potentially reveal more interesting insights. Second, due to the unavailability of data, we did not incorporate some useful variables in our assessment for urban compactness, such as floor area ratio. For some urban management decisions, these data would be extremely useful to illustrate density and urban environmental quality.

Third, it may be simplistic to use just use one variable of walking distance to public urban green space to indicate the urban green accessibility. As the Accessible Natural Greenspace Standards (ANGSs), the UK government guidance on open space access provision, specifies that urban residents shall be provided with certain sizes of green space within certain distances (Comber et al. 2008). Furthermore, quality of green space shall also be considered, such as area size, quietness, spaciousness, affordability, safety, park maintenance, and aesthetic features, and free sport facilities (Grahn 1991, Van Herzele and Wiedemann 2003, Comber et al. 2008, Grahn and Stigsdotter 2010, Fan et al. 2017). Future research may consider to have a comprehensive urban green accessibility indicator that incorporates accessibility to different levels of green space and quality, such as Fan et al. (2017) that measures how well residents are treated in terms of access to neighborhood-level (2–20 ha), district-level (20–100 ha), and city/metro-level (>100 ha) of public urban green spaces in Shanghai.

Fourth, although we had a basic understanding of types of development and their relationships to urban planning, our categorization is rather general and did not capture the co-evolved dynamics of local planning and urban development at different localities of the study area. There are 12 and 10 administrative districts, respectively in Taipei City and New Taipei City. While each district has an urban plan sub-district in Taipei City, 10 districts of New Taipei City has a total of 38 urban plan sub-districts, made our study area to have a total 50 units of urban plan sub-districts. Planning for each district has also continuously been revised. More research effort will be needed to analyze the dynamic co-evolution of development and planning and how that may affect urban compactness and green space. In this paper, we did not provide a quantitative assessment the effectiveness of planning guiding urban development. In future research, we can consider to adapt planning effectiveness indexes proposed by Wu et al. (2017) to understand more thoroughly the impact of planning.

6. Conclusions
Compact and green urban development has become increasingly attractive as a way to address the urbanization challenge. This paper defines compact and green urban development as to have dense, mix-used, connected, polycentric, accessible, and green urban format. Using a high-density Asian metropolis, Taipei, as a case, it develops a comprehensive index, urban compact-green index (UCI), to integrate five aspects of a compact urban built environment, i.e. density of residents and commercial activities, land use mix, street connectivity, access to center/subcenters, and

| ID | Name            | Center or subcenter | UCI   | UGAI   | STD_UCI | STD_UGAI |
|----|-----------------|---------------------|-------|--------|---------|----------|
| 1  | Banqiao         | Subcenter           | 0.50  | 0.49   | 0.05    | 0.11     |
| 2  | Tamshui         | Subcenter           | 0.48  | 0.49   | 0.06    | 0.13     |
| 3  | New Banqiao     | Center              | 0.52  | 0.51   | 0.03    | 0.14     |
| 4  | Yonghe          | Subcenter           | 0.49  | 0.41   | 0.05    | 0.06     |
| 5  | Xinmen–Zhongshan| Center              | 0.54  | 0.50   | 0.05    | 0.12     |
| 6  | Nanjing-Fuxing  | Subcenter           | 0.46  | 0.51   | 0.05    | 0.13     |
| 7  | Fuxing NBS      | Center              | 0.48  | 0.58   | 0.04    | 0.21     |
| 8  | Wanhua          | Subcenter           | 0.53  | 0.54   | 0.04    | 0.16     |
| 9  | Gongguan        | Subcenter           | 0.43  | 0.38   | 0.03    | 0.02     |
| 10 | Guting          | Subcenter           | 0.46  | 0.49   | 0.06    | 0.12     |
| 11 | City Hall       | Center              | 0.51  | 0.51   | 0.07    | 0.13     |
| 12 | Eastern Shopping| Subcenter           | 0.47  | 0.48   | 0.07    | 0.11     |
| 13 | Shipai          | Subcenter           | 0.44  | 0.53   | 0.04    | 0.15     |
| 14 | Jaintan         | Center              | 0.46  | 0.44   | 0.02    | 0.02     |
| 15 | Shilin          | Subcenter           | 0.43  | 0.71   | 0.04    | 0.24     |
|    | Average         |                     | 0.48  | 0.50   | 0.05    | 0.12     |
access to transit stops. In addition, urban green accessibility index (UGAI) is developed to assess the accessibility to public urban green space in the context of a high-density metropolis. We found that while great spatial variations exist among different parts of Taipei Metropolitan Area, the metropolitan area has a distinguished polycentric pattern of UCI index with three distinct clusters around the center and sub-centers that have higher UCI values. While most subcomponents reflect the spatial pattern of UCI, density index (DI) and transit stop index (TSI) have their own interesting pattern, with the highest values of DI are concentrated in Banqiao and Yonghe Districts of New Taipei City, not in Taipei City, whereas TSI has an easily recognized linear pattern. High values of UGAI appear to be along the river corridors and scattered within the entire Taipei Basin. When compared to UCI, UGAI has a similar polycentric but more dispersed spatial pattern, as well as linear patterns along river corridors. Using the outcomes of our assessment, we further compared them with the planning maps of Taipei. We identified spatial patterns of three different types of developments in New Taipei City in term of their relationship with planning, i.e. plan-induced, plan-expanded, and non-planned development. We found that most areas of medium or high UCI values are located in areas of either plan-induced or plan-expanded development. Only a very small portion of non-planned development in our study area has medium UCI values. UCI values in areas of plan-expanded development are generally higher than that of areas of plan-induced development. This implies that although urban plans have reasonably reflected the development reality, planning for new towns (urban development) has not been effective in guiding development. UCI and UGAI are spatially correlated to a certain extent. We found that most centers and one particular subcenter have high UCI and UGAI, moving towards both compactness and green accessibility. Two subcenters with high UCI and low UGAI, i.e. Banqiao and Yonghe, calls for better planning to provide green spaces for residents living in these rising subcenters.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available for legal and/or ethical reasons.

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