

Controlled urban sprawl in Auckland, New Zealand and its impacts on the natural environment and housing affordability

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Abstract

Auckland experienced phenomenal expansion since 1841. This study assesses the pace of urban sprawl and its control over the natural environment and housing affordability. After the urban built-up area was mapped, its change over time was detected, and correlated with population. From 1842 to 2014 built-up area in Auckland grew from 48 ha to 50,531 ha. The pace of growth was 151 ha/year during 1842–1945 but jumped to 989 ha per annum during 1975–2001. It dropped to only 249 ha per annum in this century. This unchecked sprawl is a direct response to population growth and facilitated by improved transportation. Since the late 1990s urban built-up areas experienced a subdued expansion despite continued population growth. This curtailed sprawl is attributed to the contentious planning regulations implemented to curtail sprawl. Consequently, population density rose to 28 persons/ha, the highest since a century ago. Urban growth has reduced biomass and green fields with mean vegetation index dropped from 129.5 to 118.7 during 2002–2014 with a smaller standard deviation, suggesting the landscape is increasingly homogenized. House prices rose slowly when the growth potential decreased slowly and vice versa ($r = -0.925$) while the number of vacant sections suitable for single dwellings declined. Thus, controlled urban sprawl is largely responsible for the skyrocketed price of sections and declined housing affordability.

Keywords: Urban sprawl, Change detection, Housing affordability, GIS analysis, Environmental impact, Auckland

1 Introduction

Urban areas are the most important geographic zone to human beings and their socio-economic activities. According to one estimate, approximately, 40% of the world's population, or around 3 billion people live in urban areas, and this percentage will increase in the future (UN-HABITAT, 2008). Unchecked urban growth will lead to grave consequences, such as congestion, air quality deterioration, loss of amenity, and reduced biodiversity and ecosystem service functions (Brody, 2013; Shao et al., 2021). In urban areas, a variety of uses are competing for precious land, including residential, commercial, industrial, recreational, and transport. The net

effect is the rapid urban sprawl that has encroached upon the adjacent rural land. Urban sprawl refers to the new development of urban areas (e.g., residential and shopping) in areas adjoining existing urban areas. The rapid expansion of urban areas requires periodic monitoring to yield up-to-date information on urban land covers and extent vital to urban planners. Such information can facilitate planning for future growth and avoiding costly planning mistakes. Timely and accurate monitoring is also very important to understand the relationships and interactions between humans and the natural environment (Feng & Li, 2012).

Urban sprawl is most efficiently monitored using remote sensing that can supply timely images current up to hours, which are especially valuable in monitoring areas of rapid urbanization and residential development. How to delineate the extent of suburban land cover

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using remote sensing caught the attention of remote sensing scientists as early as the beginning of this millennium (Epstein et al., 2002). In addition to Landsat multi-spectral scanner data (Yang & Lo, 2002), SPOT and Sentinel data have been used for this purpose (Durieux et al., 2008; Gao & Skillcorn, 1998; Jacquin et al., 2008; Phiri et al., 2020; Tong et al., 2010). The monitoring period can be extended further back if supplemented with topographic maps and large-scale cadastral maps (Kurucu & Christina, 2008), and even aerial photographs (Ma et al., 2008). Mapping of urban built-up areas is based primarily on impervious surfaces and their spatial and temporal variability (Jat et al., 2008). The generic workflow of monitoring urban growth from time-series satellite imagery involves change detection (Yang, 2011). One common method is the post-classification change detection technique through cross-tabulation (Shalaby et al., 2012). Urban sprawl can be monitored by detecting changes in the mapped extent of urban areas (Bhatta et al., 2010). Naturally, multi-temporal satellite data are ideal for this purpose (Feng & Li, 2012; Tang et al., 2006).

The monitoring of urban sprawl is most effectively accomplished in GIS that is the best at storing and reproducing various kinds of integrated geospatial data (Kurucu & Christina, 2008). This integration is able to yield quantitative measurements needed for rapidly growing regions and in identifying the spatial variations and temporal changes of urban sprawl patterns (Yeh & Li, 2001). The resulting information is presented visually in the form of urban-growth maps (Noda & Yamaguchi, 2008). Remote sensing and GIS can be used to assess the impacts of urban sprawl, such as the loss of cropland (Shalaby et al., 2012). The direct consequence of urban sprawl is the disappearance and fragmentation of forests (MacDonald & Rudel, 2005; Miller, 2012). After urban sprawl has been detected, it can be explained by its various drivers, such as population (Alsharif & Pradhan, 2014; Farooq & Ahmad, 2008). Land resource loss combined with population data allows a more nuanced interpretation of land-use change than in previous analyses of urban sprawl (Hasse & Lathrop, 2003). In addition, the environmental impact of urban sprawl has attracted much attention in the literature. For instance, Martinuzzi et al. (2007) integrated census data with satellite imagery to study the human environment of urban sprawl in Puerto Rico. Furberg and Ban (2012) assessed the potential environmental impact of urban sprawl in the Greater Toronto area. Nevertheless, this assessment focused on environmentally sensitive areas instead of the natural environment in general, such as the loss of green fields. On the other hand, such information is indispensable for urban planners in designating new areas for constructing dwellings to cater to the needs of the additional population in

years to come. However, existing studies attempted to link urban sprawl to population growth only within a time-frame of decades (Crankshaw & Borel-Saladin, 2019). Thus, the precise relationship between population and urban sprawl at different stages over a century or longer remains unexplored.

In order to minimize the negative impacts of urban sprawl such as traffic congestion and loss of biodiversity, some municipal governments around the world have attempted to contain spiralling urban expansion through zoning regulations. This attempt can curtail sprawl but can have severe implications for living quality. In particular, it may also provoke severe repercussions on housing affordability as the regulations restrict the supply of green fields for urban development. It is commonly recognized that controlled urban sprawl negatively impacts housing affordability. For instance, a greenbelt surrounding Seoul, South Korea prevented uncontrolled urban sprawl and caused the real estate prices in the inner city to soar (Dege, 2000), even though it is possible to make more housing affordable and available for low-income households (Aurand, 2013). Although sprawl and the supply of affordable housing are positively correlated for very low-income households in metropolitan areas, there is no evidence to suggest that controlled sprawl makes housing more affordable after controlling for other metropolitan characteristics are taken into account. On the other hand, significant urban sprawl in the Rocky Mountain region in the last decade by the inward migration of population did cause real estate prices to spiral (Ghose, 2004). There exists a strong positive relationship between restrictive land-use policies and house prices (Gyourko, 2009). Thus, controlled urban sprawl has opposite effects on house prices in different cities (e.g., leading to a higher price in some cities, but a lower price in other cities).

The study has three objectives: (1) to determine the rate and pattern of urban sprawling for Auckland from its initial settlement by Europeans in the 1840s to the present; (2) to comparatively evaluate and explore the pace of growth in urban built-up extent in relation to population growth and government policy on urban land use during the study period; (3) to assess the impact and implications of curtailed urban sprawl in the city on population density, the natural environment, and housing affordability.

2 Study area

The study site is the Auckland urban area located in the upper North Island of New Zealand (Fig. 1). Although Auckland encompasses an administrative area of 101,233 ha, its urban built-up area is much smaller at 7489 ha (Rankin, 1979). The majority of it is confined to an isthmus between the Waitemata and Manukau

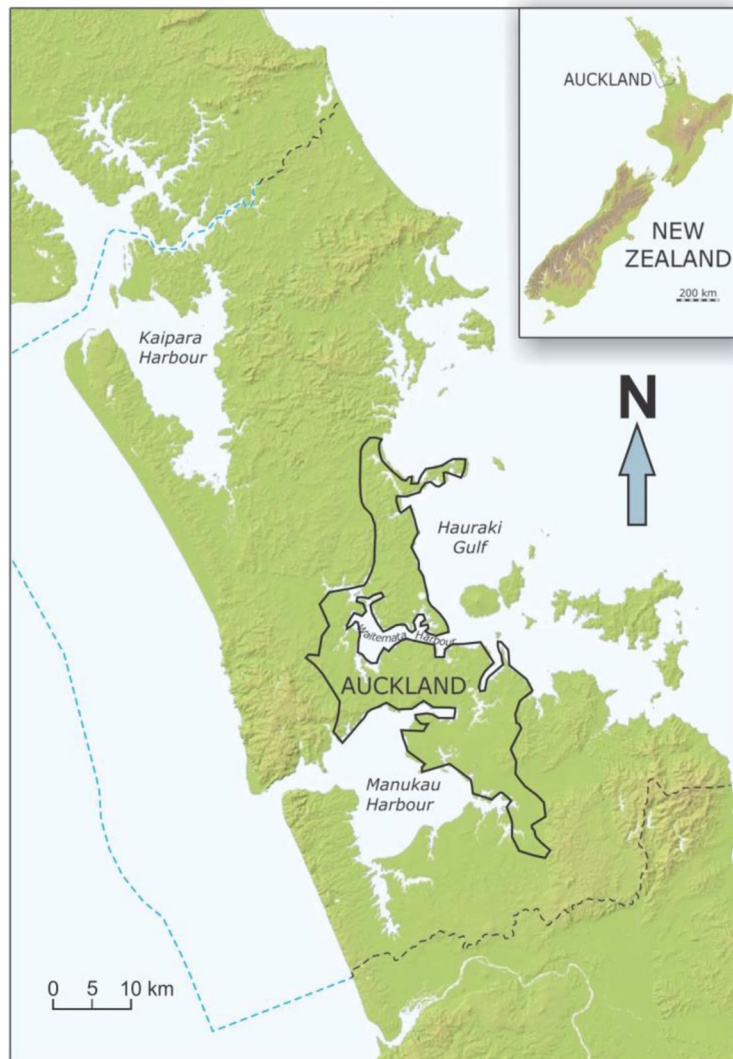


Fig. 1 Administrative boundary of Auckland and its location in the North Island of New Zealand. Solid black line: metropolitan urban limit

Harbours, spreading outwards towards the surrounding rural landscape in the north and the south. There is less population in the city's eastern and western areas where the landscape is dominated by mostly rolling mountains. Auckland used to be inhabited by the native people of Maori in the eighteenth century and was initially settled by Europeans since the early 1840s. Abundant employment opportunities and the mild weather saw the region's population grow to 1.4 million by 2013 (MacPherson, 2013), accounting roughly for one-third of the country's total population. This population is projected to grow to 1.9 million by 2031 (Statistics NZ, 2010). The arrival of more people both domestically from the province and internationally from other countries requires more housing that is achieved via converting agricultural land to residential use, which has contributed to

built-up area sprawl. Inevitably, it exerts some negative impacts on the natural environment and increases the cost of servicing the newly urbanized areas. This has prompted the local government to enact planning strategies to carefully manage such growth to minimize the impacts and to preserve living amenity. The efforts to contain urban growth have unexpected consequences on house affordability over the last decade. This area of study was chosen because it has experienced continuous urban sprawling since the city was settled by the Europeans in the 1840s, and historical land cover maps dating back then were available. Recently, the municipal government attempted to contain urbanization mostly within its current urban limit, which has caused housing prices to skyrocket. This site serves as an excellent case to study how restrictive urban planning can affect the shape

and pace of urban area development and its consequence on urban green fields and housing affordability.

3 Methodology

3.1 Data used

Four types of materials (data) were used in this study, historic town plan and land use maps, recent satellite images, census data, and real estate data. Historic town plan maps and recent land-use maps of Auckland were collected from published sources and the Auckland Regional Council. These maps show the urban extent of Auckland in nine years from 1842 to 2001. Additional land cover maps were produced from two Landsat images recorded on 18 April 2004 and 30 April 2014. More recent land covers were not analyzed due to the lack of land price data. Census data dating back from 1842 to the present were acquired from Statistics New Zealand. Since census data are collected every 5 years, the year of census data does not always coincide with the time of the land cover maps. The two can mismatch by a maximum of 2 years from each other. Real estate data of

2001–2014 are collected from the Real Estate Institute of New Zealand and Quotable Value New Zealand, the country’s largest property information company.

3.2 Data processing and analysis

The 2014 satellite data were intersected with the Auckland Metropolitan Urban Limit (Fig. 1) layer to demarcate the study site. Afterward, it was smoothed within a window of 5 by 5 pixels to iron out exceptional spectral variations within urban areas in ERDA S Imagine before it was classified. In the unsupervised classification, the number of spectral clusters varied from 12, 20 to 30 experimentally (Steinley & Brusco, 2011). During post-classification it was found that only the 30-cluster results enabled built-up areas to be mapped at a reasonable accuracy as they visually resembled the urban areas shown on the false color composite (Fig. 2). Thus, all those clusters representing urban built-up were aggregated into one class while all remaining clusters were amalgamated into another during recoding, resulting in a binary map of urban versus non-urban. Accuracy assessment based



Fig. 2 Subset color composite of bands 5 (red), 3 (green), and 2 (blue) of Landsat 8 OLI image recorded on 14 April 2014 (size: 2136 by 1833). It clearly shows urbanized areas (e.g., industrial areas in blue and residential areas in reddish blue). Blue line: metropolitan urban limit

on 60 evaluation pixels (30 urban built-up and 30 non-urban pixels) revealed that the mapping of urban areas was achieved at an accuracy higher than 95% owing to the large number of clusters specified beforehand. Thus, the unsupervised classification results were deemed satisfactory and used subsequently to detect urban sprawl.

During post-classification processing, the aggregated and recoded results were spatially filtered using clumping and sieving during which a threshold of 10 pixels (an area of 0.9 ha on the ground) was specified. Any clusters with a membership < 10 pixels were removed from the output map. This filtered layer was transformed into the vector format before being exported to ArcGIS for further editing. Extensive manual editing was undertaken to remove tiny spurious polygons and to generalize boundaries of built-up polygons. The edited vector layer was overlaid with other built-up layers of different years to illustrate the location of newly urbanized areas. The amount of their spatial extent was quantitatively determined in the table environment.

The mapped urban built-up area was statistically analyzed in relation to population in Excel to illustrate the relationship between the two. A similar analysis was undertaken for house prices. The impact of urban sprawl on the natural environment was examined through normalized difference vegetation index (NDVI), an index indicative of the amount of biomass on the ground from the red (band 4) and near-infrared (band 5) bands of Landsat 8 (bands 3 and 4 for Landsat 7). House price data were also correlated with the observed urban built-up area from satellite imagery.

4 Results

4.1 Expansion of built-up area

The initial settlement of Auckland in 1841 started from the landing at the waterfront near Britomart with most of the administrative buildings clustered around the nearby streets in close proximity to each other in 1842 (Fig. 3, left). Consequently, the built-up area was rather compact at only 48 ha. Driven by inward immigration, the formerly disunited buildings had coalesced to form continuous, mostly residential blocks that had extended westwards by 1866. These settlements, not confined to the southern shore of the Waitemata Harbor, totaled 448 ha. Such a huge amount of built-up area represented an increase of nearly 15 fold at an annual rate of 17.7 ha. Five years later built-up area expanded by 249 ha to reach 697 ha. In addition to the former waterfront site, new and isolated settlements were founded in the distant south. During the Victoria-Edwardian era (1871–1915) the built-up area swelled 10 times larger to reach 5039 ha due mostly to economic development. As the port city for the hinterland, Auckland played a pivotal role in exporting goods produced in the country such as dairy products and timber (Bloomfield, 1967). The urbanization rate was particularly high towards the late years of this period. Consequently, nearly the entire northern half of the isthmus had been urbanized.

This trend of rapid urban growth continued into the two world war era between 1915 and 1945 during which built-up area nearly tripled to 13,642 ha at an annual rate of 287 ha. While the growth was spectacular in the isthmus itself, some areas in the north, east, and south were also settled along the transport corridors. For instance, formerly isolated towns had been joined together

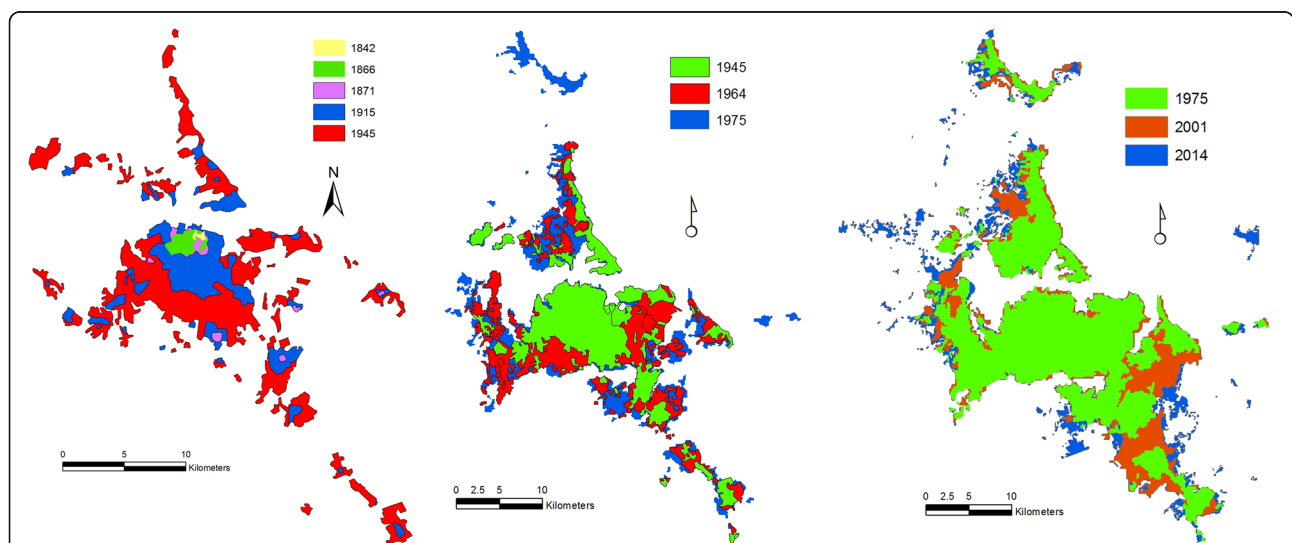


Fig. 3 The spatial extent of built-up areas in Auckland since the 1840s (Note: What is shown is the net expansion from the immediately preceding year to the current year. Thus, the urban built-up area in a later year encompasses that in all previous years). Note: The indicated years were selected because land cover maps were available for these years

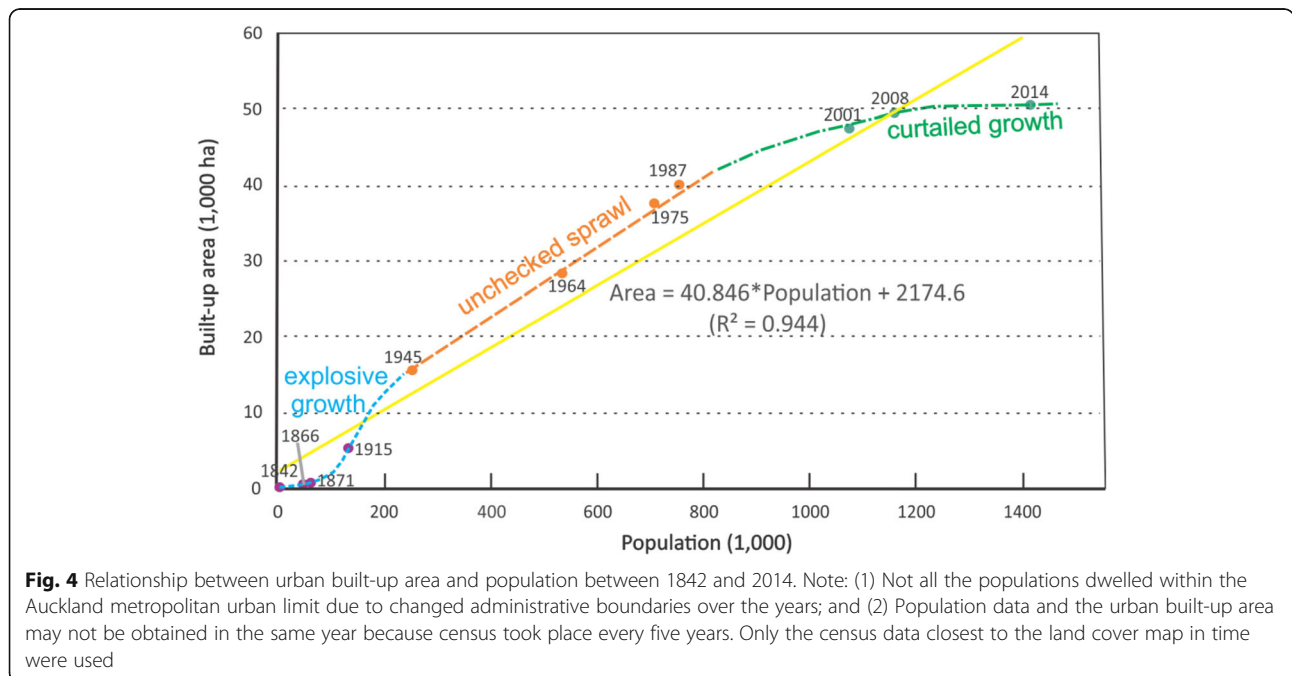
along the railway line. The built-up area nearly doubled to reach 26,793 ha at an annual rate of 692.16 ha during the post-war era of 1946 to 1964 (Fig. 3, middle). Growth was especially expansive in East Auckland, and to some degree, in the southwestern isthmus. Other newly urbanized areas were confined to the west and the south along the trunk roads and adjoining formerly settled areas. The advent of private cars and improved roads and public transport enabled suburbs much further from waterfront Auckland to be urbanized. State housing for the war veterans, together with factories spurred by the provision of electricity, was responsible largely for the expansion of built-up areas in East Auckland. This vast pace of growth was also a direct response to expanded manufacturing that created employment for thousands of new arrivals who further fueled suburban expansion (Bloomfield, 1967). During the next decade (1964–1975), the built-up area of Auckland continued its accelerated growth to reach 37,000 ha at an annual rate of 927.91 ha. As shown in Fig. 3 (right), most of the newly urbanized areas are confined to the south, the west, and the north owing to the improved transport infrastructure such as motorways. They opened up new areas for settlement. In addition, coastal areas like the east and far north had been developed, mostly for residential use due to the naturally appealing landscape. This pattern of growth is attributed mostly to the opening of the harbor bridge in 1953.

In contrast to the spectacular growth over the previous period of 1975–2001, the pace of growth during 2001–2014 is subdued. The majority of the new growth was

confined to East and South Auckland that used to be extensive and expansive flat green fields suitable for conversion to residential dwellings. The urban area rose marginally to only 49,520 ha by 2008 and 50,531 ha by 2014. Most of the newly urbanized areas during this century were situated in the north and south, all being small in size (Fig. 4, right). The expansion in the north shore further away from the coast and the northwest was related to the construction of the second bridge in the upper harbor. The rate of growth decreased from 989 ha per annum during 1975–2001 to only 249 ha per annum during 2001–2014. By 2014 the built-up area expanded by less than 200 ha per annum. Most of the newly urbanized areas are located in the south and the north of the city, nearly all of them from market gardens and pasture. They are rather small in their spatial extent, all adjoining existing built-up areas unexceptionally. Thus, the pace of expansion has slowed down to a fraction of that of decades earlier. Apparently, the unbridled urban sprawl of Auckland over the previous periods has been brought under control by this stage.

4.2 Built-up area vs population

Figure 4 illustrates the relationship between urban built-up area and population growth during 1842–2014. Overall, the two variables are highly correlated with each other ($R^2 = 0.944$). The growth pattern falls into three periods of undergrowth, unchecked growth, and curtailed growth. The first period took place in the nineteenth century when the population grew at a faster pace than built-up area expansion. There was no sprawl at all. During the



second period that covered the first 90 years of the twentieth century, both population and the urban built-up area grew slowly but steadily at an almost identical pace until 1945. Afterward, they underwent a steep rise until reaching a plateau in 1975 when both stagnated slightly following the stock market crash in 1989. The two have been growing at an almost identical rate with a high correlation between them until the 1990s. Employment opportunities and migration have seen a rapid rise in the city's population over the last two decades that has been accommodated via the ever-expanding built-up areas. According to this diagram, the 1000-fold expansion of the urban built-up area is a direct response to explosive population growth. However, entering the third period, the two trends of growth started to diverge from the 1990s when planning regulations imposed a limit on urban sprawl so as to control run-away infrastructure costs. On the one hand, the population continued to rise steeply while built-up areas rose marginally in comparison, resulting in a gently inclined curve. As clearly shown in the diagram, the effort to curtail urban sprawl is rather successful. However, this containment is achieved at the expense of reduced living amenity (e.g., a much higher population density) and social cost in that real estate price has skyrocketed beyond the affordability of many residents.

The direct impact of the curtailed sprawl is a general rise in population density that was the highest during the undergrowth period in the nineteenth century following the settlement of Auckland (Fig. 5). The highest density of 107.9 persons/ha in 1866 was attributed to the fact that little urban land was used for purposes other than residential. Industrial and recreational land use was extremely limited prior to large-scale industrialization.

The lack of proper means for transport to further afield made the city highly compact. The high density started to drop considerably about a century ago when it plunged to only 26.2 persons/ha owing to better transport and improved roads that allowed people to live away from the downtown area. From the 1960s to the 1980s it fluctuated slightly at just under 20 persons per hectare. However, population density became noticeable higher from 2001. Since then it has risen slowly but steadily, with 2014 being the highest at 28 persons/ha in a century. Such a high density derives directly from the diverging trends of change in population and urban built-up area shown in Fig. 4. This increase in density suggests that the growth of more residents in Auckland has been accommodated mostly via house infilling, which inevitably will exert an impact on living amenity and cost.

4.3 Impact on the natural environment

Urban growth can be achieved via two means, infilling and outward sprawl. The former does not cause outward growth but via intensification in the forms of subdivision and construction of more compact housing (e.g., terraced housing). Since Auckland's built-up areas comprise predominantly detached houses, infilling is possible only through a subdivision of existing sections. The net effect of new division and sub-division is reduced green space and more impervious surfaces within the metropolitan urban limit (MUL). The change from vegetated surface to impervious surface is ideally studied from NDVI. This index is quite effective in revealing the amount of biomass on the ground. A higher index value means a smaller impervious surface and vice versa. With

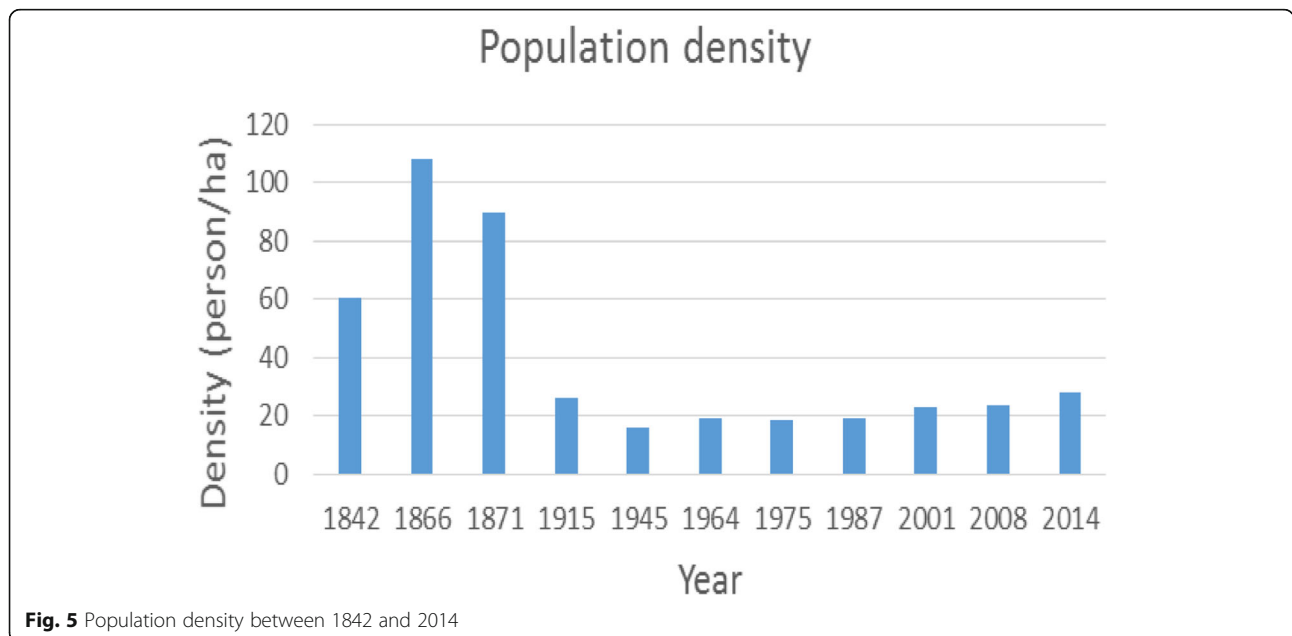


Fig. 5 Population density between 1842 and 2014

the intensification of housing, fewer green fields are left within the current urban limit, and hence a lower NDVI value.

Figure 6 visualizes the spatial distribution of NDVI values in 2004 and 2014. The two results are obtained within only 12 Julian days from each other, so the difference in NDVI between the two results caused by natural variability is reduced to a minimum. Overall, the mean NDVI value decreased from 129.5 in 2004 to 118.7 in 2014. Besides, the standard deviation of NDVI values has almost halved from 17.21 to 9.28, meaning that the landscape is becoming increasingly homogenized in its land covers (e.g., covered by concrete surfaces). The decrease in NDVI value is rather obvious at certain spots. The most noticeable is Flatbush (A) in the southeast. The former spatially expansive green area has drastically shrunk in its extent. Another noticeable area of change took place in Orewa (B) in the north. The former green area has become more fragmented with a lower NDVI value. The land has been converted mostly to residential uses with a moderate NDVI value, but also increasingly red (industrial and terraced housing with little green space between houses). The third area of considerable decrease in green fields is Henderson Creek in the west (C). Although some green fields remain, their area has shrunk with the remaining green fields more fragmented. These kinds of changes at the urban fringe took place in the form of conversion from green fields to urban uses on a wholesale scale. In addition, changes in the form of subdivisions also took place. It also reduced NDVI values, although not as significant as the new

division. Since the two NDVI maps do not have the same legend, the change in NDVI caused by house infill in the form of subdivision within built-up areas is very difficult to appreciate in Fig. 6.

4.4 Built-up area vs housing affordability

One prerequisite of urban sprawl is the conversion of rural uses such as market gardens and pasture into urban use in which the land must be divided into sections for dwelling construction, the most direct way of gauging the impact of controlled sprawl is to examine the availability of sections for sale. Shown in Fig. 7a is the dwindled supply of 350–650 m² vacant sections suitable for a single dwelling in established urban areas within a radius of 25 km from Auckland’s central business district. It experienced a steady decrease from 4116 in 2002 to only 1402 in 2012, a decrease of 65.9% (source: Quotable Value). On average, the number of vacant sections decreased by 10% annually over the decade. In other words, most of the land earmarked for urban development had been depleted quickly over the preceding unchecked period of sprawl. The dwindling supply of smaller sections than in the previous decades and/or the controlled release of more green fields for housing have contributed to the slowdown sprawling. In sharp contrast to this decline is the steady increase in the price of vacant sections during the same period (Fig. 7, top). The two are correlated inversely with each other, with 91.78% of the variations in section price (R^2) accounted for by the number of vacant sections. Section price rose from NZ\$100,000 from 2002

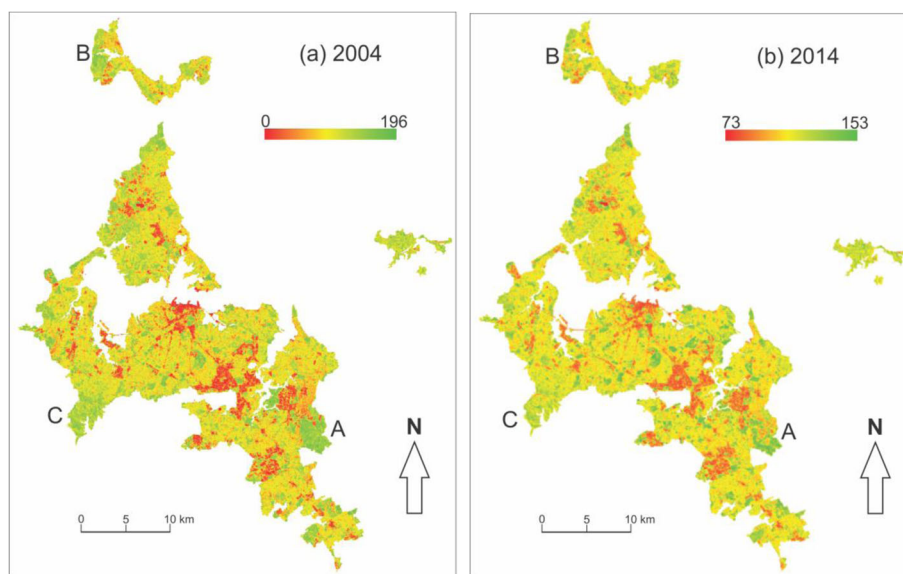


Fig. 6 Comparison of the spatial variation in NDVI for the city of Auckland. (a) 18 April 2004 (mean NDVI = 129.5; Standard deviation = 17.21); (b) 30 April 2014 (mean NDVI = 118.7; standard deviation = 9.28). Note: Some areas experienced a higher NDVI value due to the natural growth of vegetation

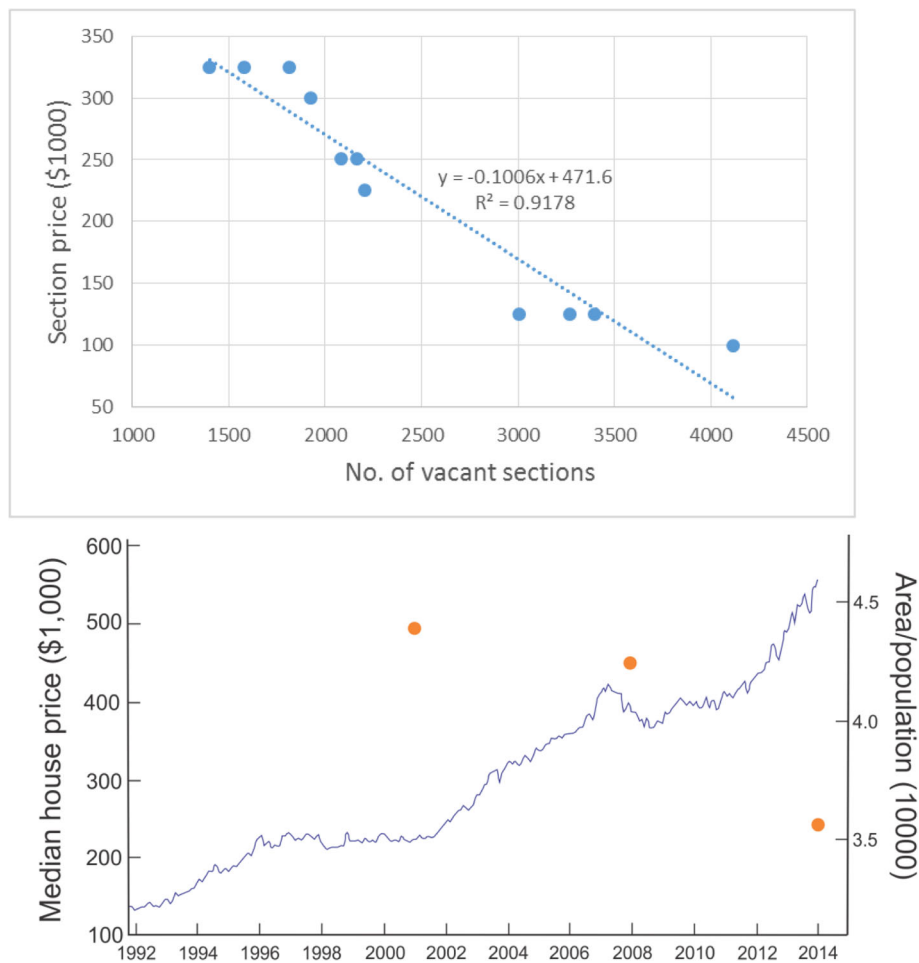


Fig. 7 Top: Scatterplot of the number of vacant sections versus section price during 2002–2012; Bottom: Median house price (blue line, left axis) during 1992–2014 versus growth potential (orange dots, right axis) in Auckland (source: Real Estate Institute of New Zealand; Quotable Value). Note: vacant sections are 350–650 m² in size suitable for a single dwelling within 25 km from the Auckland CBD

when the data became available to \$325,000 in 2012 at an annual rate of 22.5%. This more than tripling in section price drastically reduced house affordability for most people. In a market economy, price depends on supply and demand. The strong population growth in this millennium as shown in Fig. 4 against a limited supply of vacant sections can lead only to a soaring price in land and house.

In the literature drivers of urban sprawl are identified as the increasing demand for land for construction triggered by a growing population, unreasonable urban growth, and improvements in housing standards (Ma et al., 2008). Urban sprawl can also be fuelled by accessibility, informal housing practices, direct population potential, and the existence of coastal natural resources (Polyzos et al., 2013). As revealed in Fig. 4, population growth is almost the exclusive driver of urban built-up expansion during the unchecked period. Thus, the built-up area is divided by urban population to derive the unit

population area that is synonymous with *growth potential*. Namely, a large built-up area with a small population means that each section is large, and the built-up area has a huge potential for housing intensification. This index is plotted out against the median house price (Fig. 7, bottom). During 1992–2014 the median house price rose steadily (a huge portion of house price is attributed to land cost) in Auckland. It rose slowly in the 1990s, culminating in 1997. Through the early 2000s, it stayed unchanged until 2002 when it increased at a much faster pace than in the 1990s. The median house price doubled by 2008 just before the international financial crisis. However, after only a few years of hibernation, it started to rise with revenge at an unprecedented pace. House price is affected by a variety of factors, the most important being land price. Corresponding to these changes, growth potential declined only slowly during 2001–2008 when the median house price rose slowly. As house prices started to rise at a

faster pace, the decline in the growth potential also accelerated. The period of the fastest house price rise corresponds to a period of the steepest decline in growth potential (Fig. 7, bottom). Due to the small number of observations available, it is impossible to establish a quantitative regression relationship between the two. The correlation coefficient based on the three available observations is as high as -0.925 , remarkably similar to but slightly lower than that (-0.958) between the number of available vacant sections and section price. Therefore, the policy of maintaining urban growth within the existing urban limit is the main culprit of the skyrocketed housing price and abysmal housing unaffordability.

5 Discussion

The subdued increment in built-up areas in this century (Fig. 3) differs sharply from the fast rise in the preceding period, even though Auckland's population maintained the same pace of growth. The divergence of the two towards the later 1990s results from both land depletion and planning policies. In the literature, the role of critical policies in affecting urban sprawl has been noted (Yue et al., 2013). Auckland is no exception. Auckland housing used to be dominated by standalone dwellings constructed over a 'quarter acre' (1000 m^2) section in an era when the population was small and residential land bountiful. This generous land use practice was driving the unstoppable urban sprawl in the first 80 years of the twentieth century. Such unchecked sprawl overburdens establishing new and maintaining ever more infrastructure. In addition, it imposes a heavy toll on the government to provide services, such as bus, utility, and storm water treatment. More sprawl means more skyrocketed costs in providing such services in sparsely populated areas. Apparently, such an inefficient allocation of land resources for urban use is not sustainable in light of internal migration and inbound international immigration associated with globalization. This prompted the local authorities to promulgate planning regulations to limit urban sprawl so as to control run-away infrastructure costs. The policy is commonly known as Metropolitan Urban Limit that has been in existence for over half a century. This legal document sets out the rules for urban development and subdivisions to reduce runaway infrastructural costs. This zoning boundary demarcates the urban area within which urban development is allowed (Auckland Regional Growth Forum, 1999). It still exerts an impact even today as "over the next 30 years for 280,000 new dwellings within the 2010 Metropolitan Urban Limit baseline, 160,000 will be built in new green fields land, satellite towns, and other rural and coastal towns" (Auckland Council, 2012). Consequently, the land inside the MUL is around 10 times more expensive

than land just outside it (Grimes & Liang, 2009). The attempt to confine new growth mostly within the existing urban limit is directly responsible for the divergence of the two trends of growth from the 1990s onwards. Therefore, the MUL is a binding and increasing constraint on land supply at a time when housing demand has intensified (Zheng, 2013).

The desire to build a compact city with minimal impacts on the natural environment has some unexpected consequences on housing affordability. This issue can be better addressed by modifying other planning policies commensurately to accommodate the continuous influx of migrants. For instance, the minimum section size can be reduced to allow housing intensification and the restriction on building height can be relaxed to allow high-rise housing development to dent the section price. To strike a delicate balance between building a compact city and maintaining affordable housing, certain restrictions on urban development must be relaxed in light of continuous inward migration, even though these changes may degrade the amenity of existing urban areas.

Elsewhere rapid urbanization has been associated with the construction of infrastructures such as airports and highways in developing countries (Pourebahim et al., 2015). Auckland is no exception. Certainly, the considerable expansion of Auckland towards the southeast and the north (Northshore) in the 1960s and 1970s (Fig. 3) can be attributed to the completion of Auckland Southern Motorway in 1953 and the opening of the Auckland Harbour Bridge in 1959, respectively. It must be emphasized, nevertheless, infrastructure is critical to shaping the urbanized area, but it may not affect the total amount of urbanized areas critically.

6 Conclusions

Since its initial settlement by Europeans in 1842, Auckland has sprawled by 1000 folds in its built-up area to reach 50,531 ha in 2014 at an uneven pace of growth during different periods. Settled areas were small and compact in the nineteenth century owing to the lack of transport and not-so-developed economy. With the development in economic activities and the arrival of migrants from rural areas, the urban area expanded steadily in the early twentieth century, an outcome facilitated by better transport infrastructure. Auckland experienced explosive growth between the two world wars during which the built-up area nearly tripled. Urban sprawl culminated to reach an annual rate of nearly 1000 ha in the 1960s and 1970s when there was an unlimited supply of mostly flat agricultural land. The spectacular expansion in built-up areas was facilitated by improvements in transport infrastructure, including railways, motorways, and bridges. Both population and urban built-

up areas grew at the same pace until the late 1990s when growth in built-up areas was curtailed despite the continued population growth driven partially by immigration. It grew by only 3235 ha to reach 50,531 ha during 2001–2014 at a rate of 249 ha per annum, only a quarter of the rate in the preceding period. This urban growth has negatively impacted the living environment in that the NDVI, an indicator of biomass on the ground, declined from 129.5 in 2004 to 118.7 10 years later while its standard deviation became smaller as well. This indicated that the landscape is increasingly homogenized with former green fields converted to urban uses in peri-urban areas. The curtailed sprawl in this century is accounted for by the contentious planning regulation designed to contain urban growth to mostly within the existing Metropolitan Urban Limit. This regulation has caused housing increasingly unaffordable as judged by the dwindling number of vacant sections suitable for single dwellings. It bears a close correlation with section price at $r = -0.958$. The increase in the median house price experienced an exactly opposite change to that in growth potential ($r = -0.925$). The fact that the growth potential decreased slowly when house prices rose only slowly but dropped substantially when the median house price skyrocketed suggests that the effort in containing urban sprawl through legislative boundary is the primary culprit of house unaffordability. More observations are needed to quantify the exact contribution of curtailed sprawl on house price rise.

Code availability

No applicable.

Authors' contributions

Tingting Xu: 70% (did most of the data analysis); Jay Gao: 30% (wrote the manuscript and drew the illustrations).

Funding

This research was supported by an internal research grant from the University of Auckland.

Availability of data and materials

The data are satellite images available from Google Earth Engine.

Declarations

Competing interests

No conflicts of interest.

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Received: 24 May 2021 Accepted: 12 July 2021

Published online: 28 July 2021

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