Residential environments across Denmark have become both denser and greener over 20 years

Karl Samuelsson 1, Tzu-Hsin Karen Chen 1-4, Sussie Antonsen 3,5, S Anders Brantl 1, Clive Sabel 2,3 and Stephan Barthel 7,8

1 Department of Geospatial and Computer Sciences, University of Gävle, Gävle, Sweden
2 Department of Environmental Science, Aarhus University, Roskilde, Denmark
3 Danish Big Data Centre for Environment and Health (BERTHA), Aarhus University, Aarhus, Denmark
4 Department of Geosciences and Natural Resource Management (IGN), University of Copenhagen, Copenhagen, Denmark
5 Department of Economics and Business Economics, Aarhus University, Aarhus, Denmark
6 Centre for Integrated Register-based Research (CIRRAU), Aarhus University, Aarhus, Denmark
7 Department of Building Engineering, Energy Systems and Sustainability Science, University of Gävle, Gävle, Sweden
8 Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

E-mail: karl.samuelsson@hig.se

Keywords: urban densification, urban greening, remote sensing, population register, urbanisation dynamics

Supplementary material for this article is available online

Abstract

Despite much attention in the literature, knowledge about the dynamics surrounding urban densification and urban greening is still in dire need for architects, urban planners and scientists that strive to design, develop, and regenerate sustainable and resilient urban environments. Here, we investigate countrywide patterns of changes in residential density and residential nature at high spatial resolution over a time period of >20 years (1995–2016), combining a dataset of address-level population data covering all of Denmark (>2 million address points) with satellite image-derived normalised difference vegetation index (NDVI) data. Our results show that many residential environments across Denmark have witnessed simultaneous densification and greening since the mid-1990s. In fact, the most common change within 500 m neighbourhoods around individual address points is of joint increases in population and NDVI (28%), followed by increasing NDVI with stable population figures (21%). In contrast, only 8% of neighbourhoods around address points have seen a decline in either population or NDVI. Results were similar in low- middle- and high-density environments, suggesting that trends were driven by climate change but also to some degree enabled by urban planning policies that seek to increase rather than decrease nature in the cities.

Urban densification, the process of infilling the urban fabric and building upwards to increase urban density, is a strategy to prevent sprawl and achieve less energy-intensive cities while accommodating a global growing urban population [1]. However, its environmental gains have often not been properly examined [2], while it is often implicitly or explicitly considered irreconcilable with urban greening [1]. Meanwhile, nature that might be developed through urban densification provides regulating ecosystem services that are important for the wellbeing of urban residents. Green infrastructure at the metropolitan scale can provide climate change mitigation through carbon sequestering [3,4]. But more importantly, ecosystem services provide climate change adaptation, where temperature regulation and flood regulation are examples of insurance capital as extreme weather events associated with global warming become increasingly common [4–6]. Thus, the roles of ecosystem services for simultaneous climate adaptation and mitigation will likely grow, posing challenges for regional land use policies aiming at reducing car travel and urban sprawl in the midst of urbanisation [2,4,7].

The interplay between density and nature is also related to urban residents’ well-being through mechanisms operating at the local scale. Among many ways to conceive of density, we focus on density of people.
This is because city living is linked to social stress processing [8], which suggests that the higher prevalence of depression and anxiety in cities compared to the countryside [9] could be explained by exposure to many people. As an antidote to social stress, nature experience can promote health by inducing in people a state of low psychophysiological stress and restored cognitive functioning [10]. Cross-sectional evidence corroborates this interplay between experiences of social stress and restorative experiences in people’s everyday life [11], while longitudinal evidence shows that growing up in greener residential areas is linked to lower risks of adulthood mental illness [12].

While the above outlined relationships between specific environmental factors and well-being are well studied, there is a relative absence of studies looking at patterns over time of density and nature in combination. Such a perspective is urgently needed for relating long-term and global scale processes such as urbanisation and climate change to local residents’ well-being, both in terms of how they impact on everyday urban life but also with respect to how they impact on the ability to buffer disturbances that are likely to become more frequent in the future. Some previous studies exploring anthropogenic effects on urban vegetation have focused on distance from city centre [13], income [14] or compound measures of human activity [15]. A recent study found large parts of Berlin to have undergone simultaneous residential densification and greening over the last decade [16]. Here, we complement these studies by investigating patterns of residential density and residential nature over a time period of >20 years (1995–2016) across Denmark. Denmark has a population of about 5.8 million people in an area of about 43 000 km². It has a temperate climate, with most of the country located between latitudes 55° and 57° N and at the terminal section of the Gulf stream. The predominant landuse is agriculture, which is interspersed with built-up areas and forest (figure 1). Copenhagen, the capital, is the largest city, with some two million people living in the metropolitan area.

To measure residential nature, we use satellite image-derived data on the normalised difference vegetation index (NDVI), a simple arithmetic transformation of spectral data [17]. Satellite-image derived NDVI can capture detailed variability in greenness across urban landscapes [18], making it suitable to analyse long-term trends related to urban development. Studies looking specifically at NDVI over time in urban areas have found that it tends to decrease with rapid urbanisation [19] but can subsequently increase as spatial expansion slows down [13, 20]. Changes in NDVI also relate to large-scale drivers. Warmer temperatures in the temperate zone has been found to drive regional NDVI increases in the 1990s and 2000s [21, 22]. However, the correlation with temperature has seemingly decreased in recent years while the correlation with precipitation
has increased [15]. Species diversity has also been suggested as a driver in the temperate zone [23].

Rather than analysing NDVI across the complete landscape, we combine it with a dataset of address-level population data (>2 million address points) to estimate neighbourhood-scale exposure to nature [24]. This allows nationwide co-analysis with detailed measures of residential population density. In the following, we investigate neighbourhood changes in residential density and NDVI from 1995 to 2016, first across all Danish residential environments, and then broken down into categories of low-, medium- and high-residential density.

Methods

Address-level exposure
To measure population density and exposure to greenspace, individual address points were used. This data was derived from the 2016 version of the geocoded Danish Residence Database from the register of official standard addresses (for details, see [26]). We used only records with exact coordinates (~2 million addresses, or ~97% of all records within the borders of Denmark), excluding some entries where the address was recorded only within a 1 × 1 km area. For each address point and for each year 1995–2016, we calculated the number of residents and amount of greenspace within circular areas of 250, 500 and 1000 m radii (hereafter called neighbourhoods, see figure 2 for illustration).

Population density
Population density estimations are based on individual residence records from the Danish Civil Registration System as documented in the Danish Residence Database [26]. This database is maintained by Centre for Integrated Register-based Research at Aarhus University (CIRRAU) and contains the exact number of individuals at each address point. Due to Danish data protection regulations, data can only be exported from the CIRRAU data environment and co-analysed with other data after it is anonymised, posing issues with neighbourhoods with very few residents. Thus, the exact number of residents within neighbourhoods on 1 January for each year was calculated in SAS software through a series of SQL statements based on distances between points, before measurements were truncated into 50 unit bins (i.e. measurements of 0–49 persons were reassigned to 25, 50–99 persons were reassigned to 75, etc). A total of 50 unit bins were used as they ensure that measurements are anonymous in the least densely populated areas, but also retain much variation between addresses as neighbourhood measurements are often in the 100s or 1000s (figure S1, which is available online at stacks.iop.org/ERL/16/014022/mmedia). Measurements in this truncated form were then exported and co-analysed with NDVI data.

NDVI
In Google Earth Engine [27], we accessed surface reflectance Tier 1 images from Landsat-5 (TM) from 1995 to 2012 [28], Landsat-7 (ETM+) from 1998 to 2018 [29] and Landsat-8 (OLI) from 2012 to 2018 [30]. These data are at 30 m spatial resolution with systematic terrain correction and atmospheric correction, including a per-pixel cloud mask produced with the Fmask algorithm [31], allowing removal of cloud and cloud shadow pixels within Google Earth Engine. Two collections of scenes were created: first, from 1 May to 31 August, and second, from 1 July to
31 July. The reason for this was to explore and disen-
tangle trends for the majority of the growing season
and the peak of it, respectively. NDVI was calculated
from the near-infrared (NIR) and red (R) bands using
the formula \( \text{NDVI} = (\text{NIR}−\text{R})/(\text{NIR}+\text{R}) \). Per-pixel
median values were extracted from each composite to
produce annual NDVI images.

Using data from Landsat-7 (ETM+) and Landsat-
8 (OLI) in time-series can entail complications as they
are equipped with different sensors \[8\] (OLI) in time-series can entail complications as they
are equipped with different sensors \[32\]. To cali-
brate these data, NDVI values for August 2015 from
each satellite were extracted at 10 000 sample sites
across Denmark, allowing evaluation of the effects of
transforming OLI data through reduced major axis
(RMA) regression as well as ordinary least squares
regression (see \[32\]). We used the coefficients repor-
ted in Roy et al \[32\] and found RMA regression to
better adjust the underestimated reflectance in OLI
images (figure S2), and thus multiplied NDVI values
from Landsat-8 with the RMA regression coefficients
to harmonise data across the years.

To get rid of water areas that would bias neigh-
bourhood NDVI calculations, a masking layer created
from the Danish land-use land-cover map from the
year 2011 \[25\] was used (for details, see supplemen-
tary information). After removing water areas, moving
windows (function ‘local’ in \[33\]) were used to calcu-
late mean NDVI values for the three neighbourhood
scales. Because of the 30 m cell size, we used quadratic
matrices with radii of 255, 495 and 1005 m \((17 \times 17,
33 \times 33 \text{ and } 67 \times 67 \text{ cells, respectively})\) where cells
in corner areas were given no weight while remaining
cells were given weight 1 (see figure 2 for illustration).
NDVI values were joined to addresses by overlaying
rasters with address points from the Danish Residence
Database and assigning points with the value of the
overlapping raster cell.

Calculating and mapping trends of change across
Denmark

The change of the Danish population’s residential
environment was explored over the study period.
For each address point, neighbourhood residents and
NDVI within 250, 500 and 1000 m, respectively, were
regressed on time in years. As predictive capacity
was not an objective of the models, we used linear
regression, without incorporating non-linearity or an
autoregressive term. Coefficients of annual change for
each variable at each address point were extracted,
unless time did not predict a change in a variable
\((p\text{-value} > 0.05)\) when the coefficient was set to 0.

To explore combined changes in population and
NDVI, a \(3 \times 3\) matrix with the classes increasing,
stable or decreasing for each variable was used to
assign each address point a population-NDVI com-
bination. Changes in environments of different dens-
ity were explored by splitting the dataset into three
roughly equally sized population density categories
\(<400, 400–1200, \text{ and } >1200 \text{ people within 500 m}\) to investigate population and NDVI trends up until
2016 in the least, middle and most dense thirds of
neighbourhoods separately. For May–August values
and July values, respectively, median, 20th percent-
il and 80th percentile values were calculated in each
of the categories. Linear models with median values
regressed on time in years were fitted.

All results were visualised with maps of regression
coefficients across Denmark, as well as histograms,
bi-variate density plots and time series diagrams.

Validation of NDVI trends

The trends observed in our NDVI dataset were veri-
ﬁed by comparing it to three other satellite image
datasets. The methods and results of this validation
can be found in the supplementary information.

Results

As the patterns of changes within 250 and 1000 m
neighbourhood sizes did not differ considerably (see
table S1), the results section focuses on changes
within 500 m of address points (NDVI values report-
ed are median values from 1 May to 31 August unless
otherwise stated). Within 500 m neighbourhoods,
the median population has increased by 12% from
825 people in 1995–925 people in 2016 (figure 3(a)).
About 740 000 address points (35%) had stable pop-
ulation numbers—these occur in all types of settings,
but with a low median value of 225 people, indicat-
ing that neighbourhoods with unchanging popula-
tion density are mostly rural. About 870 000 address
points (42%) had a significant increase, while about
475 000 (23%) had a significant decrease. The dens-
ity of these environments largely overlap; the median
in the increase group went from 1025 to 1275 people
\((+24\%)\), while the median in the decrease group
went from 1125 to 975 people \((-13\%)\). Changes
in population are geographically unevenly spread
across Denmark (figure 4). The largest increases have
occurred in central parts of larger cities, whereas
the largest decreases have mostly occurred in fringe
suburban areas of larger cities. Thus, population
flows in Denmark since 1995 has not been an
urbanisation process in its classical meaning (see
\[34\]), as the overall share of urban dwellers has not
increased much.

NDVI fluctuates considerably from year to year,
but overall there is a clear increasing trend: residen-
tial environments in Denmark has become greener
(see figure 3(b) for histograms and figure 5 for a
map). The mean regression coefficient times the
number of years of the study period amounts to 0.028
\((a 7\% \text{ increase})\). Most of this increase occurred in the
latter half of the 1990s. A total of 1.33 million address
points \((64%)\) had a significant increase, while only
44 000 \((2\%)\) had a significant decrease. The NDVI val-
ues of these groups largely overlap. 710 000 address
points \((34\%)\) had stable NDVI values; these areas had
on average higher values than both increasing and decreasing areas, as can be seen when comparing the green and grey areas in figure 3(b).

In terms of combined changes of population and NDVI, classified as either increasing, stable or decreasing, all combinations are represented (table 1). However, joint increases is the most common combination (roughly 580 000 address points), >100 times more common than joint decreases, the least common combination (roughly 5600 address points). Joint increases is the most common combination in the large cities but also appear in other environments, whereas increasing populations coupled with stable or decreasing NDVI is found in some areas of new development in cities, stable populations coupled with any NDVI change is found mostly in rural areas, and decreasing populations with increasing NDVI is found in fringe suburban areas of cities (figure 6).

In 1995, about 665 000 points (32%) had a neighbourhood population below 400. The median population in this category stayed stable at 75 in both 1995 and 2016, while the median NDVI increased from 0.45 to 0.51. About 675 000 points (32%) had a population from 400 to 1200. The median population in this category increased from 755 in 1995–875 in 2016, while the median NDVI increased from 0.41 to 0.47. About 750 000 points (36%) had a population above 1200. The median population in this category increased from 1975 in 1995–2075 in 2016, while the median NDVI increased from 0.36 to 0.41. These changes are shown in figure 7(a). Linear fits for median values regressed on time in years are significant for all categories for the period May–August (figure 7(b)) but for no categories for only July (figure 7(c)), indicating that despite generally increasing NDVI there has not been an increase in peak period greenness. A visual inspection

![Figure 3](image-url)

**Figure 3.** (a) Histogram of number of people within 500 m of address points in 1995 and 2016, colour coded by whether the trend has been increasing, decreasing or stable between 1995 and 2016. Each address point thus belongs to the same category in both histograms. Black vertical lines show the median value at the current year. The median has increased by 12% from 825 people in 1995–925 people in 2016. Data points in the eight lowest bins have been randomly reassigned to a number within their bin to give the histogram a smoother appearance (e.g. data points in the lowest bin were reassigned to a random value 1–49). (b) Histogram of mean NDVI within 500 m of address points in selected years from 1995 to 2016, colour coded by whether the trend has been increasing, decreasing or stable between 1995 and 2016. Each address point thus belongs to the same category in both histograms. Black vertical lines show the median value at the current year.

| Population | Increasing | Stable | Decreasing |
|------------|------------|--------|------------|
| Increasing | 580 364 (28%) | 268 501 (13%) | 21 494 (1%) |
| Stable     | 430 431 (21%) | 300 821 (14%) | 17 383 (1%) |
| Decreasing | 319 716 (15%) | 149 786 (7%) | 5599 (0%) |

*Table 1.* 3 × 3 matrix of combined changes in population and NDVI within 500 m neighbourhoods. Numbers are the number of address points with that particular combination of change, with percentages of all address points stated within brackets.
Figure 4. Annual change in people within 500 m of address points, as modelled through linear regression. Insets show (A): Aarhus, (B): Copenhagen, and (C): Odense, all at the scale given in inset (A). Intervals were set based on equal number of observations in each class, but manually modified to have rounded breakpoints and be symmetrical around 0.

Figure 5. Annual change in mean NDVI within 500 m of address points, as modelled through linear regression. Insets show (A): Aarhus, (B): Copenhagen, and (C): Odense, all at the scale shown in inset (B). Intervals were set based on equal number of observations in each class, but manually modified to have rounded breakpoints and be symmetrical around 0.
of the trends seems to suggest a browning from 2001 to 2007 and then greening again from 2007 to 2016, especially in denser environments. The trend is smoother with less oscillations in denser environments compared with less dense, which is reflected in better linear model fits. Trends for the 20th and 80th percentiles in each category follow the medians closely. These results overall suggest that residential environments across Denmark have generally become greener, irrespective of population density and despite continued densification.

Discussion

Our main result is counter-intuitive when imagining a spatial trade-off between residential densification and residential greening. We found that residential environments down to the level of neighbourhoods surrounding individual address points across all of Denmark have generally become both denser, in terms of residential population, and greener, in terms of NDVI, since the mid-1990s. This study complements those by Persson et al [14], that revealed a greening trend in Stockholm, Jin et al [13] and Du et al [20], that revealed greening in some Chinese cities, and Wellmann et al [16], that showed how Berlin has also undergone simultaneous densification and greening. However, to our knowledge, this analysis is the first to show a nationwide consistent greening trend in densifying urban environments around individual address points where the urban residents live.

Potential reasons for densification and greening across Denmark

One of our main findings is that NDVI changes have been generally positive, regardless of neighbourhood residential density or greenness. This calls into question whether the trends revealed in this study is attributable to factors unrelated to the built environment. Denmark has like most of the world got warmer in recent decades; the temperature average between 2006–2015 was 1.2 °C higher than the 1961–1990 average [35]. The NDVI trend observed in this study resembles a large-scale greening-browning-greening pattern across the northern hemisphere during 1982–2012 [15]. Increasing NDVI >35° N in the nineties can largely be attributed to increasing temperatures [21]. Warmer weather has led to longer growing seasons in Europe [36–38]. However, the relative importance of temperature as a driver has decreased over the last decades while the relative importance of precipitation has increased [15]. As climate change unfolds and temperature becomes less of a limiting factor for plant growth in northern Europe, variability in precipitation will likely increase both within and across years [39]. This calls into question how urban planners and landscape architects can adapt...
to this development by creating green infrastructure that thrive in variable precipitation conditions and at the same time build resilience towards extreme weather events [5].

Even though NDVI change is affected by global drivers, land-use and spatial planning also matter. This might explain why Denmark’s rural areas display divergent patterns (figure 5). NDVI has increased most in mainland Denmark’s central and southwestern parts that consist of sandy outwash plains. These areas have been the target for policies aiming to double the area of forest [40] and restore wetlands [41]. The rest of Denmark mostly have soils of clayey tills where many rural areas do not show an NDVI increase. For example, on the island Samsø (located between (A) and (C) in figure 5), the forested areas are stable, whereas areas of NDVI decrease could reflect agriculture shifting to less green crops. Between 2011 and 2016, Samsø’s total agricultural area was largely constant, but grass and potato cultivation decreased with 18% and 15%, respectively, and grain cultivation increased with 19% [42]. Similar developments may explain NDVI decreases in many rural settings throughout eastern Denmark.

Median NDVI throughout the summer has increased uniformly in the vast majority of urban areas even as residential density has also increased in many of these. However, we did not find evidence for an increased peak period greenness, suggesting that longer growing seasons accounted for most greening throughout the summer and that any areal increase or maturation of urban greenspace is small in comparison. However, trends driven by large-scale climatic variables might be complemented by urban

Figure 7. Population and NDVI within 500 m of address points stratified by three categories of residential environments based on whether the population in 1995 was below 400, from 400 to 1200, or above 1200. (a) Shows density plots of population and NDVI throughout summer in 1995 and 2016. The coloured dots show median values for the three different categories of residential environments and arrows show how they changed between 1995 and 2016. All three categories have seen a marked increase in NDVI. (b) Shows May–August median values (filled lines), and the 20th and 80th percentile (dashed lines) in each category. Fitted linear regressions are shown as dotted lines with standard error margins as filled areas. Pearson correlation coefficients and p-values of fits are shown in lower right corner. (c) Shows the same statistics as in (b) but values are for only July. Unlike May–August values, there is no evidence of an increase in peak period greenness.
planning policies that seek to enhance blue-green elements in already built-up environments (see for example [43]). The building volumes of Copenhagen and Aarhus underwent only modest horizontal and vertical expansion since 1987 while their populations grew [44]. The flow of people from suburban to inner-city areas could be seen as a reaction towards active planning for dispersion in the decades leading up to the nineties [45]. Moreover, Copenhagen has due to active interventions in its infrastructure witnessed a biking revolution since the nineties, with some 50% of journeys in the city now being carried out by bike [46]. This might have freed up some impervious surfaces for greening, as seems to have been the case in other greening cities [13].

In summary, even though climate change is reasonably the main driver behind greening in Denmark, the fact that Danish residential environments have also become denser might have been enabled due a shift in urban planning policy from a focus on spatial expansion to one of increasing rather than decreasing natural land in the cities. As a comparison, Berlin achieved simultaneous densification and greening by converting industrial land, brownfields or roads [16]. This provides some encouragement from the global perspective, as most large cities around the world have recently undergone spatial expansion [47] associated with detrimental urban encroachment on carbon pools, biodiversity and fertile farmlands [48, 49], and might now be in a position to switch course. Yet, the added pressure on well-being for urban populations that climate change presents is not evenly shared across the world, nor across social classes within each city [50]. Also, while urban citizens of the Global South are expected to disproportionately be impacted by climate change, the greening of neighbourhoods in the Global North is in part possible because natural resources are withdrawn from distant ecosystems by way of social-ecological teleconnections [51]. This calls for integrated systems assessments on scales from the local to the global in the area of urbanisation and land-use intensification.

Limitations and further work
The processed dataset post anonymisation does not contain information on residents at individual address points, but only on the number of residents within neighbourhoods. In most single-family houses, residents per address point would be 2–5 people, but in large multi-story buildings, this might be hundreds of people. Thus, even though we can determine how residential environments themselves have changed over time, we cannot in detail answer the question how neighbourhood population density or NDVI has changed for the average resident in Denmark. We can, however, with confidence say that most residents have experienced simultaneous densification and greening of their home environment. This is because address points in neighbourhoods with larger populations as a general rule will have more people living at them, so these environments would have been ‘weighted heavier’ in an individual-unit analysis. Future work could link these neighbourhood measurements to individuals to study health outcomes. From the point of view of advancing theory around stress reduction [52], attention restoration [53] and biophilia [54], it would be illuminating to study areas that have seen increases in both NDVI and people. The biophilia hypothesis predicts that these areas have become more conducive to well-being, while stress reduction theory and attention restoration theory predicts that there could be some breakpoint where negative impacts from stress induced by crowding outweighs the positive impacts from sensory interaction with natural features.

Our study is ecological in nature, meaning that we investigate average neighbourhood changes. The utility of this approach rests on a ‘proximity argument’, i.e. that individuals are exposed to the environment in which they live. This could be refined by using personalised sensors (see [55, 56]) to understand the daily trajectories of people, to move from ecological measures to individualised exposure and provide a better understanding of to what extent and under what circumstances the ‘proximity argument’ holds for modelling real-life exposure.

Conclusion

With space in cities being a limiting resource, scholarly discussion around urban sustainability is still often framed in a simplistic dichotomous fashion, which hampers understanding of what makes urban neighbourhoods resilient from the point of view of urban residents’ well-being [11]. With increasing availability of large high-resolution spatiotemporal datasets and better methods for extracting information relevant for urban life from these datasets [44], we are better suited than ever to conduct multivariable dynamic analyses of the urban environment. Herein, we have presented a methodologically relatively simple yet high-resolution analysis of residential density and residential nature across Denmark. We not only uncovered an expected large variation between different neighbourhoods, but also to us, a surprising yet robust result: over a period of ca. 20 years the general trend across Danish neighbourhoods has been of simultaneous increasing population density and greening. Furthermore, migration within Denmark has been characterised more by population flows from suburbs/exurban areas to inner-city areas, rather than between rural and urban areas. However, all kinds of residential environments in Denmark have become greener over the past decades, even those kinds where most population growth has occurred. Crucially, this is not a net result of some areas densifying and others greening but is true of neighbourhoods around individual address points.
We realise that the capacity to respond to global processes and the pressure on urban well-being that climate change presents is not evenly shared across the world, nor across social classes within each nation \(^{[50]}\). Yet, our results lend support to the possibility that cities in industrialised nations can become both denser and greener. Most large cities still plan for the automobile, resulting in urban encroachment on biodiversity-rich land and fertile farmlands with detrimental impacts on both local well-being and the global Earth system. However, as this is to our knowledge the first nationwide analysis at the level of individual address points, it is possible that the patterns we found can also be found elsewhere. We welcome further investigations as these results provide much needed encouragement for sustainable urbanisation around the world.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

The script used for downloading NDVI data in Google Earth Engine can be found here: https://code.earthengine.google.com/10e03693709 ac04d84f1a33a79b538

All R scripts used to prepare data, calculating values around addresses, and performing regressions can be found here: https://github.com/kallesam/dk_pop_nat

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We appreciate the valuable input from Carsten Boeker Pedersen, Ingo Fetzer and Adrian Baggsström in discussions around the design and implementation of this research. K S was supported by FORMAS Grant No. 2016-01193. T-H K C was supported by a PhD scholarship from the Taiwanese Ministry of Education, and T-H K C and C S were supported by BERTHA—the Danish Big Data Centre for Environment and Health funded by the Novo Nordisk Foundation Challenge Programme (Grant No. NNFI70OC0027864). K S and T-H K C designed the research with input from C S and S B; K S, T-H K C and S A prepared the data; K S and T-H K C performed the analysis; and K S, T-H K C, S A, S A B, C S and S B wrote the paper.

ORCID iDs

Karl Samuelsson \(\circ\) https://orcid.org/0000-0002-7936-3722

Tzu-Hsien Karen Chen \(\circ\) https://orcid.org/0000-0002-0343-6147
S Anders Brandt \(\circ\) https://orcid.org/0000-0002-3884-3084
Clive Sabel \(\circ\) https://orcid.org/0000-0001-9180-4861
Stephan Barthel \(\circ\) https://orcid.org/0000-0003-2637-2024

References

[1] Haaland C and van den Bosch C K 2015 Challenges and strategies for urban green-space planning in cities undergoing densification: a review Urban For. Urban Green. 14 766–71
[2] Gren Å, Colding J, Berghauser-Pont M and Marcus I 2019 How smart is smart growth? Examining the environmental validation behind city compaction Ambio 48 580–9
[3] Jansson Å and Nohrstedt P 2001 Carbon sinks and human freshwater dependence in Stockholm county Ecol. Econ. 39 361–70
[4] Pan H, Page J, Zhang L, Cong C, Ferreira C, Jonsson E, Näsström H, Destouni G, Deal B and Kalantari Z 2020 Understanding interactions between urban development policies and GHG emissions: a case study in Stockholm region Ambio 49 1313–27
[5] Gómez-Baggethun E and Barton D N 2013 Classifying and valuing ecosystem services for urban planning Ecol. Econ. 86 235–45
[6] Lehmann I, Matthey J, Rößler S, Bräuer A and Goldberg V 2014 Urban vegetation structure types as a methodological approach for identifying ecosystem services—application to the analysis of micro-climatic effects Ecol. Indic. 42 58–72
[7] Colding J, Gren Å and Barthel S 2020 The incremental demise of urban green spaces Land 9 162
[8] Lederbogen F et al 2011 City living and urban upbringing affect neural social stress processing in humans Nature 474 496–501
[9] Peen J, Schoevers R A, Beekman A T and Dekker J 2010 The current status of urban-rural differences in psychiatric disorders Acta Psychiatr. Scand. 121 84–93
[10] Markевич I et al 2017 Exploring pathways linking greenspace to health: theoretical and methodological guidance Environ. Res. 158 301–17
[11] Samuelsson K, Colding J and Barthel S 2019 Urban resilience at eye level: spatial analysis of empirically defined experiential landscapes Landsc. Urban Plan. 187 70–80
[12] Engemann K, Pedersen C B, Arge L, Tørgårdinnis C, Mortensen P B and Svenning J C 2019 Residential green space in childhood is associated with lower risk of psychiatric disorders from adolescence into adulthood Proc. Natl Acad. Sci. USA 116 5188–93
[13] Jin J, Gergel S E, Lu Y, Coops N C and Wang C 2019 Asian cities are greening while some North American cities are browning: long-term greenspace patterns in 16 cities of the Pan-Pacific region Ecosystems 23 383–99
[14] Persson Å, Eriksson C and Löhmus M 2018 Inverse associations between neighborhood socioeconomic factors and green structure in urban and suburban municipalities of Stockholm county Landsc. Urban Plan. 179 103–6
[15] Liu Y, Li Y, Li S and Motesharrei S 2015 Spatial and temporal patterns of global NDVI trends: correlations with climate and human factors Remote Sens. 7 13233–50
[16] Wellmann T, Schug F, Haase D, Pfugmacher D and van der Linden S 2020 Green growth? On the relation between population density, land use and vegetation cover fractions

Environ. Res. Lett. 16 (2021) 014022
in a city using a 30-years Landsat time series *Landsc. Urban Plan.* 202 (2022) 103857

[17] Weier J and Herring D 2000 Normalized difference vegetation index (NDVI)

[18] Ke Y, Im J, Lee J, Gong H and Ryu Y 2015 Characteristics of Landsat 8 OLI-derived NDVI by comparison with multiple satellite sensors and in-situ observations *Remote Sens.* Environ. 164 298–313

[19] Sun J, Wang X, Chen A, Ma Y, Cui M and Piao S 2011 NDVI indicated characteristics of vegetation cover change in China's metropolises over the last three decades *Environ. Monit. Assess.* 179 1–14

[20] Du J, Fu Q, Fang S, Wu J, He P and Quan Z 2019 Effects of rapid urbanization on vegetation cover in the metropolises of China over the last four decades *Ecol. Ind.* 107 105458

[21] Tucker C J, Slayback D A, Pinzon J E, Los S O, Myeni R B and Taylor M G 2001 Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999 *Int. J. Biometeorol.* 45 184–90

[22] Lamchin M, Lee W K, Jeon S W, Wang S W, Lim C H, Song C and Sung M 2018 Long-term trend and correlation between vegetation greenness and climate variables in Asia based on satellite data *Sci. Total Environ.* 618 1089–95

[23] He K and Zhang J 2009 Testing the correlation between beta diversity and differences in productivity among global ecoregions, biomes, and biogeo graphical realms *Ecol. Inform.* 4 93–98

[24] Gascon M, Cirach M, Martinez D, Dadvand P, Valentin A, Plasencia A and Nieuwenhuijzen M J 2016 Normalized difference vegetation index (NDVI) as a marker of surrounding greenness in epidemiological studies: the case of Barcelona city *Urban For. Urban Green.* 19 88–94

[25] Levin G, Iosub C-I and Jepsen M R 2017 Basemap02, technical documentation of a model for elaboration of a land-use and land-cover map for Denmark

[26] Pedersen M G 2018 Geocoding of Danish addresses from the residence database version 2016

[27] Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Erten J V et al 2016 Global land cover mapping from space using the Landsat program *Remote Sens. Environ.* 198 6–25

[28] U.S. Geological Survey 2018 Landsat 4–5 TM level-2 data products—surface reflectance

[29] U.S. Geological Survey 2018 Landsat 7 ETM+ level-2 data products—surface reflectance

[30] U.S. Geological Survey 2018 Landsat 8 OLI/TIRS level-2 data products—surface reflectance

[31] Zhu Z and Woodcock C G 2012 Object-based cloud and cloud shadow detection in Landsat imagery *Remote Sens.* Environ. 116 30–40

[32] Roy D P, Kovalskyy V, Zhang H K, Vermote E F, Yan L, Kumar S S and Egorov A 2016 Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity *Remote Sens. Environ.* 185 57–70

[33] Etten J V et al 2020 Package ‘raster’

[34] Megranahan G and Satterthwaite D 2014 Urbanisation concepts and trends (*International Institute for Environment and Development*) pp 1–27

[35] Cappelen J 2018 DMI rapport 18–01 Danmarks klima 2017— with English summary

[36] Kim Y, Kimball J S, Zhang K and McDonald K C 2012 Satellite detection of increasing Northern Hemisphere non-frozen seasons from 1979 to 2008: implications for regional vegetation growth *Remote Sens. Environ.* 121 472–87

[37] Garonna I, de Jong R, de Wit A J W, Műcher C A, Schmid B and Schaezman M E 2014 Strong contribution of autumn

[38] Jeppesen C, Dash J and Atkinson P M 2014 Remotely sensed trends in the phenology of northern high latitude terrestrial vegetation, controlling for land cover change and vegetation type *Remote Sens. Environ.* 143 154–70

[39] Rajczak J and Schär C 2017 Projections of future precipitation extremes over Europe: a multimodel assessment of climate simulations *J. Geophys. Res. Atmos.* 122 10773–800

[40] Mikkelsen S H, Larsen S N, Vangsgaard L B, Ravn P N and Halvorsen L B 2014 Natur og Miljø 2014—Miljøstøtten rapporter

[41] Hoffmann C C and Baattrup-Pedersen A 2007 Re-establishing freshwater wetlands in Denmark *Ecol. Eng.* 30 157–66

[42] Olggaard M V and Pedersen B F and Dalgaard T 2018 Landbrugskarakteristik for Samsø

[43] Riegg N, Lynggaard-Jensen A, Krogsgaard Jensen J, Gerner N V, Anzaldua G, Mark O, Butts M and Birk S 2020 Making the ecosystem services approach operational: a case study application to the Aarhus River, Denmark *Sci. Total Environ.* 707 155836

[44] Chen T-H K, Qiu C, Schmid M, Xiang S, Sabel C E and Prischepova A V 2020 Mapping horizontal and vertical urban densification in Denmark with Landsat time-series from 1985 to 2018: a semantic segmentation solution *Remote Sens. Environ.* 251 112096

[45] Bamford G 2009 Urban form and housing density, Australian cities and European models: Copenhagen and Stockholm reconsidered *Urban Policy Res.* 27 357–56

[46] Kaarstrøm O R and Streikovski N 2020 Cultural evolution of sustainable behaviors: pro-environmental tipping points in an agent-based model *One Earth* 2 85–97

[47] Mahnta R, Mahendra A and Seto K C 2019 Building up or spreading out? Typologies of urban growth across 478 cities of 1 million+: *Environ. Res. Lett.* 14 124077

[48] Seto K C, Güneralp B and Hutyra L R 2012 Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools *Proc. Natl Acad. Sci.* USA 109 16083–8

[49] Bren d’Amour C, Reitsma F, Baiocchi G, Barthel S, Güneralp B, Erb K-H, Haberl H, Creutzig F and Seto K C 2017 Future biodiversity and carbon pools *Proc. Natl Acad. Sci.* 114 201606036

[50] Anderson P, Charles-Dominique T, Ernston H, Anderson E, Goodness J and Elmqvist T 2020 Post- apartheid ecologies in the city of Cape Town: an examination of plant functional traits in relation to urban gradients *Landsc. Urban Plan.* 193 106622

[51] Barthel S, Isendahl C, Vis B N, Drescher A, Evans D L and van Timmeren A 2019 Global urbanization and food production in direct competition for land: leveraging places to mitigate impacts on SDG2 and on the Earth system *Anthropol. Rev.* 6 205301961985667

[52] Ulrich R S, Simons R F, Losito B D, Fiorito E, Miles M A and Zelmon S 1991 Stress recovery during exposure to natural and Taylor M G 2001 Higher northern latitude normalized difference vegetation index and growing season from 1985 to 1999 *Int. J. Biometeorol.* 35 472–87

[53] Prishchepov A V 2020 Mapping horizontal and vertical urban densification in Denmark with Landsat time-series from 1985 to 2018: a semantic segmentation solution *Remote Sens. Environ.* 251 112096

[54] Donaire-Gonzalez D et al 2019 ExpoApp: an integrated system to assess multiple personal environmental exposures *Environ. Int.* 126 494–503

[55] Loh M et al 2017 How sensors might help define the external exposome *Int. J. Environ. Res. Public Health* 14 434