

Disparities in greenspace access during COVID-19 mobility restrictions

Lusseau, David; Baillie, Rosie

Published in: Environmental Research

Link to article, DOI: 10.1016/j.envres.2023.115551

Publication date: 2023

Document Version Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA): Lusseau, D., & Baillie, R. (2023). Disparities in greenspace access during COVID-19 mobility restrictions. *Environmental Research*, 225, Article 115551. https://doi.org/10.1016/j.envres.2023.115551

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.

- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.



Contents lists available at ScienceDirect

Environmental Research



journal homepage: www.elsevier.com/locate/envres

Disparities in greenspace access during COVID-19 mobility restrictions

David Lusseau^{a,*}, Rosie Baillie^b

^a National Institute for Aquatic Resources, Technical University of Denmark, Kgs. Lyngby, 2800, Denmark ^b School of Biological Sciences, University of Aberdeen, Aberdeen, AB24 2 TZ, UK

ARTICLE INFO

Keywords:

Pandemic

Green space

Urban ecology

Human ecology

Socioecology

SDG10

SDG11 SDG15

Handling Editor: Jose L Domingo

Computational human ecology

ABSTRACT

More than half of the human population lives in cities and therefore predominantly experience nature in urban greenspace, an important contributor to wellbeing. As the world faces a pandemic which threatens the physical and mental health of billions of people, it is crucial to understand that all have the possibility to access nature exposure to alleviate some of these challenges. Here, for the first time, we integrate data from Facebook, Twitter, and Google Search users to show that people looked for greenspace during COVID-19 mobility restrictions but may not have always managed to reach it. We used a longitudinal approach, replicated in three European cities, to assess whether people spent more time in locations with more greenspace, and whether this change in urban density remained for the whole pandemic, pre-vaccine, period. We coupled this human density study with a longitudinal study of web search patterns for Parks and online discussion about urban greenspace. People searched for Parks near them more during the pandemic, particularly when they were allowed to visit them. They discussed in positive terms greenspace particularly more at the start of the pandemic. People spent more time in areas with greenspace when they could and that depended on the level of multiple deprivation of their neighbourhood. Importantly, while people sought greenspace throughout the first 20 months of the pandemic, this preference intensified through the waves of lockdown. Living in an affluent area conferred a greenspace advantage in London and Paris but we find that in Berlin greenspace in more deprived neighbourhoods were used more. Overall, urban greenspace occupied a greater place in people's lives during the pandemic. Whether people could realise greenspace access depended on the deprivation level of the neighbourhood. Public greenspace access should be integrated in national indices of deprivation given its importance for wellbeing.

1. Introduction

Over the past decade the link between access to some vegetated space or waterbodies in the urban landscape (greenspace) and both physical and mental health has become apparent (Fuller et al., 2007; Gianfredi et al., 2021; O'Connor et al., 2021; Putra et al., 2021; Two-hig-Bennett and Jones, 2018; Wheeler et al., 2015; Zhang et al., 2020). Studies have been able to disentangle greenspace exposure from physical activity confounding effects to show that exposure to features of wild and urban nature-rich spaces has an effect on physical, mental and social health (Birch et al., 2020; Bratman et al., 2019, 2015; Cohen-Cline et al., 2015; Hartig et al., 2014; Putra et al., 2021; Richardson et al., 2013; Zhang et al., 2018). These features include both habitats and species (Fuller et al., 2007; Hedblom et al., 2017; Hoyle et al., 2019; Luck et al., 2011) which coproduce these benefits with a wide range of human activities from sports to simple contemplation (Raymond et al., 2018). There are however inequalities in greenspace access and

greenspace quality associated with deprivation (Mitchell and Popham, 2008; Nesbitt et al., 2019) and urban plan features (Song et al., 2021) of neighbourhoods. Also, people can only access greenspace when they have free time coinciding with when the space is freely and safely accessible (Burnett et al., 2021; Shan, 2020; Shoari et al., 2021).

More than half the human population now lives in cities (Lederbogen et al., 2011) and therefore has regular access to nature and its cultural ecosystem services (Hirons et al., 2016) only in these anthropogenic landscapes (Birch et al., 2020; Luck et al., 2011; Mancini et al., 2019). It is therefore crucial to understand how people use greenspace to maximise the equitable provision of the health benefits it confers. Indeed, this is a key 2030 target for the United Nations Global Goal (SDG) 11. While we can estimate in many cities where greenspace is, we generally lack an understanding of its accessibility and access (Song et al., 2021).

Survey-based studies have shown that people have tended to seek greenspace more during the mobility restrictions associated with the first wave of the SARS-CoV-2 pandemic (COVID-19) in several countries

https://doi.org/10.1016/j.envres.2023.115551

Received 23 December 2022; Received in revised form 13 February 2023; Accepted 21 February 2023 Available online 24 February 2023

^{*} Corresponding author. *E-mail address:* davlu@dtu.dk (D. Lusseau).

^{0013-9351/© 2023} The Authors. Published by Elsevier Inc. This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

(Day, 2020; Lu et al., 2021; Venter et al., 2021, 2020; Zhu and Xu, 2021). Greenspace use during the pandemic conferred wellbeing advantages (Larson et al., 2022). However, there were inequalities in the ability to realise this increased interest in greenspace, and some people spent less time in greenspace despite understanding its health importance (Burnett et al., 2021).

This counterfactual show that realised greenspace use is complex and equitable access is likely affected by deprivation factors. COVID-19 offered, unfortunately, a unique natural experiment to assess the interest of people for greenspace and their ability to meet this need throughout the multiple waves of the pandemic. Here we used the unique Facebook Population data from the Data for Good programme (Maas et al., 2019) to assess whether people used greenspace more over the pandemic period depending on mobility restrictions (Fig. S1) in three European capital cities: London, Paris, and Berlin. Those cities were selected because both indices of multiple deprivation (IMDs) (Atkinson, 2003) and curated public greenspace data were openly available (see Methods) at a spatial resolution relevant to understand the socioecological context of human mobility (Alessandretti et al., 2020).

For the first time, we assess how the distribution of people in relation to greenspace in cities changed over the whole span of the pre-vaccine COVID-19 pandemic period. Changes in human density where greenspace occur could emerge from multiple contributing factors. If people are to seek greenspace exposure, they will search for its availability first (Phillips et al., 2022). We therefore also assessed whether web searches for urban greenspace changed during this pandemic period. Finally, we assessed whether self-reporting of urban greenspace experiences on social media changed during the phases of the pandemic. We anticipate that topics discussed in relation to greenspace on Twitter would change to reflect how people seek to use it (Erskine et al., 2021; Plunz et al., 2019).

This integrative computational human ecology study aims to longitudinally relate change in human density in urban greenspace to inferred motivation to use these spaces and realised experiences with the overall view to determine whether these experiences are equitably realised in neighbourhood of varying deprivation levels. By replicating these analyses in three cities we aimed to widen our inferential foundation to determine whether the observed responses to the mobility restrictions associated with the pandemic responses were similar across socio-cultural diversity or indeed whether specificities emerged.

2. Materials and methods

2.1. Sampling the change in population density

Facebook has more than 2 billion daily users and provides the broadest social media coverage of individuals across socioeconomic and demographic dimensions ensuring we can capture a more representative sample of people living in the sampled cities. Facebook population aggregated and georeferenced data was made available through an academic license agreement with the Facebook Data for Good programme (Maas et al., 2019) (https://dataforgood.fb.com/tools/disease-prevent ion-maps/). This data is available upon request for research purposes through the same procedure from the programme. Data was available for Berlin (2 Apr, 2020 to 31 Aug 2021), Paris (26 Apr, 2020 to 31 Aug 021) and London (4 Apr, 2020 to 31 Aug 2021).

2.2. Observational units

The Facebook population data aggregates the number of the app users that have their location history enabled to 'tiles'. A 'tile' is a quadrat of specific size of which the resolution depends on population density to ensure user anonymity (Maas et al., 2019). In large cities this corresponds to quadrat with sides of about 300–500 m (depending on latitude), a relevant scale for human urban mobility (Alessandretti et al., 2020). The Facebook population is sampled in three 8-h bins. Here we

used the Facebook Z-score value to estimate how different from 'normal conditions', that is pre-pandemic times, the population density was on a particular day and for a particular time bin (Maas et al., 2019) (Fig. 1). This gave us a direct measure of whether a tile was used more than "normal" during the pandemic. The Z-score value is literally the Z-score for the observed Facebook population density of a tile given the observed densities at the same time period and on the same days in the control period (Maas et al., 2019); it gives an idea of how many standard deviation away from 'normal' a tile density value is, with a positive value representing an increase in density and a negative value a decrease in density. There could be an association between the Z-score and the proportion of greenspace in a tile simply due to people being restricted to their homes and residential areas potentially having more greenspace. We therefore run two sets of models, one looking at the variation in the Z-score of tile for the daytime period 08:00-16:00 (Z₀₈) and one contrasting this Z-score to the Z score for the night-time period 00:00-08:00 (Z_{08-00}) , time at which we are sure that most people were most likely to be at home. If the greenspace effect was only caused by the increased propensity of staying at home during lockdowns, then we should not see a greenspace effect on this latter measure.

2.3. Public data covariates

We used the Oxford COVID-19 Government Response Tracker (Hale et al., 2021) to determine for each city and on each day whether people were free to move (no public health interventions), were recommended to not leave their home, or were required to not leave their home (also called lockdowns) (Fig. S1).

We could determine the proportion of greenspace and the median index of multiple deprivation for each tile. Indices of multiple deprivation (IMDs) had different definition in each city, but these differences captured the variability in the national macro socioeconomic notions of deprivation. All indices considered dimensions of access, demography and income but with measures deemed relevant to each country. Importantly, none considered greenspace access. We therefore carried out analyses on each city separately, but with a comprehension that changes in IMD could be relatively interpreted in a similar manner in each city (a deprived area in Paris may look different from a deprived area in London, but both can be considered disadvantaged). In all three cities, a tile's proportion of greenspace and IMD did not co-vary (correlation, p: London: 0.08, Paris: 0.18, Berlin: 0.09). Greenspace data was available from open public data ("Espaces verts et assimilés - data.gouv. fr," n.d.; "OS Open Greenspace | Greenspaces in urban and rural areas Vector Map Data | Free Download," n.d.; "Urban Green Space," 2021) when those were included, we removed cemeteries from the greenspace spatial data. For indices of multiple deprivation we used IMD at the LSOA level for London ("Indices of Deprivation - London Datastore," n. d.), FDep for Paris at the IRIS level ("Indice de défavorisation sociale (FDep) par IRIS," n.d.) as the first eigenvector of a weighted principal component analysis of the data available in following standard procedure (Pornet et al., 2012), and the Status index component of MSS (PLR level) for Berlin ("Status-Index, 2019 - [WMS] | Offene Daten Berlin," n.d.). The latter is a 4-level categorical variable, while the two former ones are continuous.

2.4. Facebook population density model

We developed general linear mixed effects models accounting for the repeated daily sampling of tiles as crossed random effects of tiles and date and assuming a Gaussian error structure for the response variables Z_{08} and Z_{08-00} . To ask questions about changes in daytime density (Z_{08}) and changes on contrast between daytime and nighttime (Z_{08-00}), the same sets of explanatory variables equations where fitted in model with Z_{08} and Z_{08-00} as response variables respectively (Tables S3–S5). Those models assessed whether the variance in the Z scores, given the model structure described above, was associated with the greenspace cover of



Fig. 1. Changes in Facebook population density in Berlin, Paris and London during the day (average Z-score, Z₀₈) compared to pre-pandemic levels during the first period when people were required not to leave home (March–May 2020 'lockdown') and during subsequent lockdowns over the study period (post September 2020 'lockdowns', see Fig. S1 for details).

tiles and whether this association depended on the multiple deprivation level of the tile. Models were then further developed to assess whether those associations depended on the mobility restrictions in place (3 levels, Fig. S1), the wave of restrictions during the pandemic (two or three waves depending on the city), and whether the day was a weekend day. The more complex model including a 5-way interaction between those terms (Tables S3–S5). Those were fitted using lme4 (Bates et al., 2015) in R. We then engaged in model selection (using AIC_c) where we challenged alternative hypotheses that lockdown effects depend on the other factors with data. After model selection and validation, effects were interpreted from tables of contrasts and visualisation of model predictions.

2.5. Population density in greenspace rich locations

We also developed two ancillary model sets. The first one assessed whether greenspace-rich tiles (main urban parks and gardens) were more visited during the day (Z_{08}) when people were required to stay at home. Greenspace-rich tiles were defined as tiles for which the proportion of greenspace cover was greater than the 90% quantile of the distribution of this variable in each respective city (Fig. S2b).

Berlin is in a special case where uninhabited forests are located close to the city and are not accounted as urban greenspace by the municipality. The second set therefore assessed from where people visiting forests in the Berlin district came. To do so, we used the Facebook movement data (Galeazzi et al., 2021) which quantifies changes in movement between tiles compared to pre-pandemic movement rate (Z-score). We identified forested tiles in the Berlin district ("Verwaltungseinheiten der Berliner Forsten - [WFS] | Offene Daten Berlin," n. d.), which do not qualify as urban public greenspace and are not categorised as such in the Berlin greenspace data, and determine the proportion of tiles covered in forests. We then identified the MSS status of tiles from which people visiting forested tiles came. We finally assessed whether the movement Z_{08} depended on the MSS of the starting tile and the proportion of forest at the arriving tile. Berlin's greenspace and forest data were accessed thanks to available tailored API code (Hausmann, 2021).

2.6. Online search behaviour

If a tile-level association between changes in population density and greenspace emerged from behavioural changes, we expected that people would express their motivation to seek greenspace in a manner associated with this enacted behaviour. We therefore sampled the greenspace discourse on social media. A first cue would be changes in search patterns. We searched Google Trends ("Google Trends," n.d.) for the period 30 August 2018 to 30 August 2021 for the Topic "Park". Trends Topics are an efficient shortcut to deploy a multilingual regular expression search for terms associated with a topic often searched. We limited those searches to the highest spatial resolution available for the three cities: England for London, Berlin region for Berlin, and region Île-de-France for Paris. For this timespan, the temporal resolution of relative search volume was a week. The values represented relative weekly search volume for the Park Topic, where the week with the largest volume was assigned by Google Trends a value of 100, and all others are scaled to be between zero (no weekly searches) and 100. Given this value is continuous and bounded, we divided the value by 100 and assumed beta-distributed residuals when modelling its variance. We then fitted generalized mixed effect models to this relative search prevalence assuming an autocorrelation structure in searches, with a lag of 1 week within cities using glmmTMB (Brooks et al., 2017). This autocorrelation structure provided valid residual distributions. We first assessed whether during the COVID-19 period (Mar 2020-Aug 2021) searches differed depending on the lockdown measures in the cities (using the Oxford COVID-19 GRT categorical variable). We then assessed whether search volume differed during the COVID-19 period outside of lockdown periods compared to the control period (Sept 2018-Mar 2020).

2.7. Online discussion topics related to greenspace

We searched archived tweets geo-located in the three cities using the academic track of the Twitter API for tweets mentioning Parks in the three relevant languages. This severely censored the number of tweets returned, as most users do not allow geolocation of their tweets, but it ensured that the sampled tweets originated from the cities. We then assessed whether the number of tweets posted depended on mobility

usual text preparation procedures (Roberts et al., 2019). This stm

implementation use a latent Dirichlet allocation model to jointly esti-

mate topics of discussion from the set of tweets we retained (clustering

tweets based on word prevalence) and how topic prevalence changes

with, in our case, mobility restriction. Finally, we assessed whether

public response to tweets varied with mobility restriction as well. We

estimated whether the number of likes tweets received depended on the

mobility restriction phase during which they were posted. We fitted

restrictions and waves of restrictions for each city using a generalized linear model assuming a lag of 1 day autocorrelation structure and a negative binomial error distribution implemented in glmmTMB. The best model was selected using AIC. We then fitted structured topic models (stm) (Roberts et al., 2019) to the text of tweets in each cities, assessing whether topic prevalence depended on mobility restrictions levels (Fig. S1). Before stm model fitting to the data, the text was cleaned and stemmed and emoji and emoticons were translated to text following

London - week days

London - weekend



Fig. 2. Predicted difference in Z-score (Z_{08-00}) in London, Paris, and Berlin when people were required to stay home (with exceptions) in relation to greenspace coverage and the cities' indices of multiple deprivation (red: deprived, blue: average, green: affluent) over waves of restrictions (panel 1, 2 and 3) depending on whether the day is a weekend or not. Error bands are 95% confidence intervals. See Tables S3–S5 for model selection.

generalized linear mixed effect models using glmmTMB assuming a negative binomial error structure and including a random effect of tweet topics (defined using the previous stms) to ensure that the effect of topic attractiveness was discounted.

3. Results

3.1. Urban mobility and greenspace

Given the health benefits of greenspace exposure, we expected that the richer in greenspace a tile was, the more people sought it during all mobility restriction periods, but that this effect would depend on the time people had available for leisure (Alves et al., 2013). Hence, assuming people used greenspace in their neighbourhood (Alessandretti et al., 2020), we would expect increased use during weekends everywhere, and at all times in affluent areas. We first found that greenspace rich tiles, associated with the main parks and gardens in the cities, were similarly used more during the first lockdown than in subsequent ones except in Paris where parks and gardens were closed by decree during the first wave (Nikolli and Girault, 2021) (Fig. S2, Tables S1–S2).

We found that for all three cities, variance in Z_{08} and Z_{08-00} could be best explained by the same model which considered the effect of lockdown measures to depend on greenspace coverage, IMDs, and whether it occurred on a weekend (Figs. S3-S8). However, there was substantial variance in all three cities associated with lockdown waves (Fig. 2). The patterns observed during the first lockdown did not repeat in subsequent ones. Through time, tile density decreased in all cities. The pattern of lockdown waves differed between the cities. In London, the preference for greenspace in affluent areas observed in the first lockdown waned in subsequent waves while the preference observed in deprived areas in Berlin increased, particularly in weekends (Fig. 2). There was a tendency for preference for tiles depending on their greenspace coverage to increase with tile affluence in Paris, but that effect was disparate between the COVID-19 waves. This difference further reinforces the observed associations being driven by greenspace access as Paris closed access to its greenspace during the first wave (Nikolli and Girault, 2021).

Berlin has large forest parks in its district which are not curated as greenspace because they are managed by a federal agency. It may therefore be that individuals from affluent neighbourhoods used these forests more than greenspace in their neighbourhood. We found that forests were used significantly more than usual by people originating from deprived areas (Fig. S9), particularly over weekends. Forests were visited significantly less than usual by people from affluent areas during weekdays. Berlin has neighbourhood-embedded open access community gardens (Rosol, 2010). It may be that this unique feature helped explain the greater propensity for public access to greenspace in more deprived areas in this city during the lockdowns.

3.2. Urban greenspace discourse

People searched more for the Park topic during COVID-19 (outside of lockdowns) than they did in the same weeks over the 18 months before the pandemic started (Fig. 3a) and they searched significantly more for the 'Park' topic using the Google search engine outside of lockdowns during COVID-19 (mobility restriction levels 0 & 1: Fig. 3b). This effect was the same across all three cities (Tables S8–S9). People predominantly searched to find out whether parks were opened (top queries associated with the Topic in those periods).

Qualitatively, people talked more about enjoying time in parks on Twitter during the lockdowns in all three cities (tweet topics in English, French, and German; Figs. S10-S12). However, the volume of discourse about parks on Twitter was complex. It depended on the mobility restriction waves in London while it was constant over the pandemic in Berlin and Paris (Fig. 4). There is no support for an effect of lockdown condition and lockdown wave in Paris and Berlin (best models is a constant average number of tweets, Table S10), conversely to London (restriction: $\chi_2^2 = 60.2$, p < 0.00001; wave: $\chi_2^2 = 6.0$, p = 0.05; restriction x wave: $\chi_4^2 = 153.0$, p < 0.00001). The conversation volume significantly decayed with waves in London and was lower during time of lockdowns (Fig. 4). Yet, tweets about parks during lockdowns received on average significantly more likes in all three cities (Fig. S13). As we focussed here on geolocated tweets, a small fraction of all tweets, and the proportion of the French and German population using Twitter is substantially smaller than the British Twitter population, inferences from the results for Berlin and Paris are much less certain.

4. Discussion

Not all greenspace was used in the same manner during the first 20 months of the pandemic. People sought greenspace, searched online for access and commented positively on its use, particularly after lock-downs. As we progressed through the three infection waves, and their



Fig. 3. Predicted weekly Google Trends in the 'Park' Topic contrasting the (a) COVID-19 period (Mar 2020–Aug 2021) to the control period (Aug 2018–Mar 2020) (Table S8) and (b) the periods exposed to different mobility restriction measures (Table S9). Searches were significantly more common during COVID-19 and within COVID-19 when people were not confined to their homes. Predictions from generalized mixed effect model, assuming beta distributed errors and 1-lag autocorrelation between weeks among cities.



Fig. 4. Predicted daily number of tweets about Parks in (a) London, (b) Paris, and (c) Berlin based on a generalized mixed effects model, for each city, assuming a negative binomial distribution of the tweet count residuals and a lag-1 autocorrelation structure between days. Mobility restriction: 0: "no measures", 1: "recommend not leaving house", 2: "require not leaving house with exceptions".

associated mobility restrictions, people spent less time in the three cities overall, a general movement pattern detected in other studies (Galeazzi et al., 2021). Despite this decline in density, greenspace prevalence at a location explained why that location retained more people during the day. Those that stayed spent more time in locations that had more greenspace during the day (Z_{08-00}) . However, how they achieved that depended on the level of deprivation of the neighbourhood. In London, only affluent neighbourhoods saw an increase in use with greenspace, while it decreased in deprived neighbourhoods. The difference between neighbourhoods decreased during the weekend, yet overall affluent areas retained, at all times, a greenspace advantage. The greenspace advantage was also observed in Paris, however it disappeared during the weekend. This effect was reversed in Berlin where during the first two waves it appears that people density in affluent neighbourhoods did not change during the day compared to the nights; i.e., people stayed at home, but greenspace preference was observed in more deprived neighbourhoods. Indeed, larger forested parks in the district were also more visited by people from more deprived areas.

As we contrast London, Paris, and Berlin it is worth stressing that measures deemed to capture multiple deprivation in Berlin do differ from the other two cities; with a stronger emphasis on who the inhabitants are, particularly whether they are immigrants, rather than infrastructure availability. While immigration status may capture some measures of present socioeconomic status (SES), it masks the richness of SES experience of individuals prior to their arrival in Berlin which would be key in shaping greenspace use (Thompson et al., 2008). Indeed, the immigration status dimension of IMDs in Berlin played a role in individual vulnerability to public health interventions and seem to have been a key contributor to greenspace use decisions (Collins et al., 2022).

While our longitudinal associative study provides population-level insights, we were not able to follow individuals throughout the study period. At each sampled period in the Facebook data, a user will be assigned to one tile (in rare instance two) where they have spent the most time in that period. So we are not capturing transient behaviour in greenspace exposure. For example, individuals traveling from home to daytime destinations could choose paths that would provide them with greenspace exposure during their urban commute. We are not able to capture such behaviour. While we are able to relate greenspace access intentions (web searches) to realised greenspace access (change in population density) to some qualitative understanding of the motivations to visit greenspace (topics of online discussions), we are still limited to average tendencies. We therefore cannot demonstrate a causal relationship between search, greenspace occupancy and ecosystem services received and how this relationship changes depending on the socioeconomic status of individuals.

Our longitudinal approach complements the insights generated by individual surveys to show that levels of deprivation is a key factor influencing how greenspace can be accessed when needed. While greenspace availability may be equitable across levels of deprivation by design, the ecosystem services those areas can provide can still be unequal (Chen et al., 2022). Affordance plays a key role in this. The same infrastructure may not be able to deliver the same health benefits because needs differ (Lennon et al., 2017; Roe et al., 2017) or because there is a mismatch between availability and demand (Zhang et al., 2017). Greenspace access can decrease stress in deprived areas (Ward Thompson et al., 2012); a mediator for many of the non-communicable diseases that are more prevalent in these urban locations (Marmot and Bell, 2019). Yet, to date, there is no information available on how to best design greenspace depending on neighbourhood characteristics to maximise health benefits. As the pandemic continues, and as some countries implement greenspace exposure as health interventions (Antonelli et al., 2021: Drinkwater et al., 2019), we must pay more attention to the heterogeneity of urban greenspace use associated with deprivation.

5. Conclusions

This integrative computational human ecology study is in line with traditional survey studies, which had a more limited temporal and spatial scope: people sought greenspace more than usual during the pandemic. However, the intensive large-scale sampling on which this study could rely shows that the relationship to greenspace during the pandemic was complex. First, people adapted their greenspace experience to mobility restrictions and reported using more of their cultural ecosystem services during lockdowns when they were available. The association of the change in population density to greenspace cover increased through the waves of restrictions, but where we had more observations, the online discussions about their use decreased. At all times, a neighbourhood's deprivation explained how people used greenspace in that neighbourhood and it seemed to be associated with an affordance issue.

If we are to take seriously the wellbeing contributions of greenspace and follow the indications from this study that people generally sought urban greenspace more at a time of wellbeing deterioration, then we need to formally introduce it in our planning toolkit. Our results show that greenspace design must strive to increase affordance in deprived areas and greenspace access, a clear sought and crucial urban infrastructure, must be reported as a dimension of deprivation to better plan for a sustainable urban life. This means including public greenspace access as a dimension of deprivation in national statistics like the indices of multiple deprivation we used here. This means using social media to understand how people aim to use specific greenspaces and design them to maximise their cultural ecosystem service provision, tuned to the neighbourhood's needs. This also means increasing equitability in greenspace access, to ensure that people with deprivation-related constraints can still receive greenspace exposure (Marx and More, 2022; Wood et al., 2022).

Author statement

David Lusseau: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualisation; Roles/Writing – original draft; Writing – review & editing. Rosie Baillie: Conceptualization; Investigation; Methodology; Writing – review & editing.

Materials & Correspondence

Correspondence and material requests should be addressed to DL (davlu@dtu.dk).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: David Lusseau was funded by the Independent Research Fund for Denmark (Danmarks Frie Forskningsfond). Rosie Baillie was funded by a NERC QUADRAT PhD studentship NE/S007377/1.

Data availability

The authors do not have permission to share data.

Acknowledgements

This study was funded by Danmarks Frie Forskningsfond. RB was supported by a NERC QUADRAT PhD studentship NE/S007377/1. We thank the Facebook Data for Good Programme, particularly Alex Pompe, for providing access to the COVID-19 Facebook Population density and movement data and fruitful discussions on how to best use it. We would also like to thank Twitter for the development of the Twitter API for Academic Research product.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.115551.

References

- Alessandretti, L., Aslak, U., Lehmann, S., 2020. The scales of human mobility. Nature 587, 402–407. https://doi.org/10.1038/s41586-020-2909-1.
- Alves, L., Silva, S., Severo, M., Costa, D., Pina, M.F., Barros, H., Azevedo, A., 2013. Association between neighborhood deprivation and fruits and vegetables consumption and leisure-time physical activity: a cross-sectional multilevel analysis. BMC Publ. Health 13, 1103. https://doi.org/10.1186/1471-2458-13-1103.
- Antonelli, M., Donelli, D., Carlone, L., Maggini, V., Firenzuoli, F., Bedeschi, E., 2021. Effects of forest bathing (shinrin-yoku) on individual well-being: an umbrella review. Int. J. Environ. Health Res. 1–26. https://doi.org/10.1080/ 09603123.2021.1919293.
- Atkinson, A.B., 2003. Multidimensional deprivation: contrasting social welfare and counting approaches. J. Econ. Inequal. 1, 51–65. https://doi.org/10.1023/A: 1023903525276.
- Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using Ime4. J. Stat. Software 67. https://doi.org/10.18637/jss.v067.i01.
- Birch, J., Rishbeth, C., Payne, S.R., 2020. Nature doesn't judge you how urban nature supports young people's mental health and wellbeing in a diverse UK city. Health Place 62, 102296. https://doi.org/10.1016/j.healthplace.2020.102296.
- Bratman, G.N., Anderson, C.B., Berman, M.G., Cochran, B., de Vries, S., Flanders, J., Folke, C., Frumkin, H., Gross, J.J., Hartig, T., Kahn, P.H., Kuo, M., Lawler, J.J., Levin, P.S., Lindahl, T., Meyer-Lindenberg, A., Mitchell, R., Ouyang, Z., Roe, J.,

Scarlett, L., Smith, J.R., van den Bosch, M., Wheeler, B.W., White, M.P., Zheng, H., Daily, G.C., 2019. Nature and mental health: an ecosystem service perspective, Science Advances. Am. Assoc. Adv. Sci. https://doi.org/10.1126/sciadv.aax0903.

- Bratman, G.N., Hamilton, J.P., Hahn, K.S., Daily, G.C., Gross, J.J., 2015. Nature experience reduces rumination and subgenual prefrontal cortex activation. Proc. Natl. Acad. Sci. USA 112, 8567–8572. https://doi.org/10.1073/pnas.1510459112.
- Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Mächler, M., Bolker, B.M., 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R Journal 9, 378–400. https://doi.org/10.32614/rj-2017-066.
- Burnett, H., Olsen, J.R., Nicholls, N., Mitchell, R., 2021. Change in time spent visiting and experiences of green space following restrictions on movement during the COVID-19 pandemic: a nationally representative cross-sectional study of UK adults. BMJ Open 11, e044067. https://doi.org/10.1136/bmjopen-2020-044067.
- Chen, Y., Ge, Y., Yang, G., Wu, Z., Du, Y., Mao, F., Liu, S., Xu, R., Qu, Z., Xu, B., Chang, J., 2022. Inequalities of urban green space area and ecosystem services along urban center-edge gradients. Landsc. Urban Plann. 217, 104266 https://doi.org/10.1016/j. landurbplan.2021.104266.
- Cohen-Cline, H., Turkheimer, E., Duncan, G.E., 2015. Access to green space, physical activity and mental health: a twin study. J. Epidemiol. Community Health 69, 523–529. https://doi.org/10.1136/jech-2014-204667.
- Collins, C., Haase, D., Heiland, S., Kabisch, N., 2022. Urban green space interaction and wellbeing – investigating the experience of international students in Berlin during the first COVID-19 lockdown. Urban For. Urban Green. 70, 127543 https://doi.org/ 10.1016/j.ufug.2022.127543.
- Day, B.H., 2020. The value of greenspace under pandemic lockdown. Environ. Resour. Econ. 76, 1161–1185. https://doi.org/10.1007/s10640-020-00489-y.
- Drinkwater, C., Wildman, J., Moffatt, S., 2019. Social prescribing. BMJ 364, 11285. https://doi.org/10.1136/bmj.11285.
- Erskine, E., Baillie, R., Lusseau, D., 2021. Marine Protected Areas provide more cultural ecosystem services than other adjacent coastal areas. One Earth 4, 1175–1185.
- Espaces verts et assimilés data.gouv.fr. [WWW Document]. n.d. URL. https://www.data.gouv.fr/fr/datasets/espaces-verts-et-assimiles/, accessed 10.5.21.
- Fuller, R.A., Irvine, K.N., Devine-Wright, P., Warren, P.H., Gaston, K.J., 2007. Psychological benefits of greenspace increase with biodiversity. Biol. Lett. 3, 390–394. https://doi.org/10.1098/rsbl.2007.0149.
- Galeazzi, A., Cinelli, M., Bonaccorsi, G., Pierri, F., Schmidt, A.L., Scala, A., Pammolli, F., Quattrociocchi, W., 2021. Human mobility in response to COVID-19 in France, Italy and UK. Sci. Rep. 11, 13141 https://doi.org/10.1038/s41598-021-92399-2.
- Gianfredi, V., Buffoli, M., Rebecchi, A., Croci, R., Oradini-Alacreu, A., Stirparo, G., Marino, A., Odone, A., Capolongo, S., Signorelli, C., 2021. Association between urban greenspace and health: a systematic review of literature. Int. J. Environ. Res. Publ. Health 18, 5137. https://doi.org/10.3390/ijerph18105137.
- Google. Trends [WWW Document], n.d. . Google Trends. URL https://trends.google.co m/trends/?geo=DK. accessed 9.30.21.
- Hale, T., Angrist, N., Goldszmidt, R., Kira, B., Petherick, A., Phillips, T., Webster, S., Cameron-Blake, E., Hallas, L., Majumdar, S., Tatlow, H., 2021. A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker). Nat. Human Behav. 5, 529–538. https://doi.org/10.1038/s41562-021-01079-8.
- Hartig, T., Mitchell, R., de Vries, S., Frumkin, H., 2014. Nature and health. Annu. Rev. Publ. Health 35, 207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443.

Hausmann, P., 2021. Convert WFS Data from the Berlin Geodata Portal "FIS-Broker. Hedblom, M., Knez, I., Ode Sang, Å., Gunnarsson, B., 2017. Evaluation of Natural Sounds

- Hedblom, M., Knez, I., Ode Sang, A., Gunnarsson, B., 2017. Evaluation of Natural Sounds in Urban Greenery: Potential Impact for Urban Nature Preservation, vol. 4. Royal Society Open Science, 170037. https://doi.org/10.1098/rsos.170037.
- Hirons, M., Comberti, C., Dunford, R., 2016. Valuing cultural ecosystem services. Annu. Rev. Environ. Resour. 41, 545–574. https://doi.org/10.1146/annurev-environ-110615-085831.
- Hoyle, H., Jorgensen, A., Hitchmough, J.D., 2019. What determines how we see nature? Perceptions of naturalness in designed urban green spaces. People and Nature 1, 167–180. https://doi.org/10.1002/pan3.19.
- Indice de défavorisation sociale (FDep) par IRIS [WWW Document], n.d. URL. https ://public.opendatasoft.com/explore/dataset/indice-de-defavorisation-sociale-fdep -par-iris/information/?flg=fr&q=croix&location=13, 50.67628,3.13308&basemap=jawg.streets (accessed 10.5.21).
- Indices of Deprivation London Datastore. n.d. URL. https://data.london.gov.uk/datase t/indices-of-deprivation. accessed 10.5.21.
- Larson, L.R., Mullenbach, L.E., Browning, M.H.E.M., Rigolon, A., Thomsen, J., Metcalf, E. C., Reigner, N.P., Sharaievska, I., McAnirlin, O., D'Antonio, A., Cloutier, S., Helbich, M., Labib, S.M., 2022. Greenspace and park use associated with less emotional distress among college students in the United States during the COVID-19 pandemic. Environ. Res. 204, 112367 https://doi.org/10.1016/j. envres.2021.112367.
- Lederbogen, F., Kirsch, P., Haddad, L., Streit, F., Tost, H., Schuch, P., Wüst, S., Pruessner, J.C., Rietschel, M., Deuschle, M., Meyer-Lindenberg, A., 2011. City living and urban upbringing affect neural social stress processing in humans. Nature 474, 498–501. https://doi.org/10.1038/nature10190.
- Lennon, M., Douglas, O., Scott, M., 2017. Urban green space for health and well-being: developing an 'affordances' framework for planning and design. J. Urban Des. 22, 778–795. https://doi.org/10.1080/13574809.2017.1336058.
- Lu, Y., Zhao, J., Wu, X., Lo, S.M., 2021. Escaping to nature during a pandemic: a natural experiment in Asian cities during the COVID-19 pandemic with big social media data. Sci. Total Environ. 777, 146092 https://doi.org/10.1016/j. scitotenv.2021.146092.

- Luck, G.W., Davidson, P., Boxall, D., Smallbone, L., 2011. Relations between urban bird and plant communities and human well-being and connection to nature. Conserv. Biol. 25, 816–826. https://doi.org/10.1111/j.1523-1739.2011.01685.x.
- Maas, P., Iyer, S., Gros, A., Park, W., McGorman, L., Nayak, C., Dow, P.A., 2019. Facebook disaster maps: aggregate insights for crisis response & recovery. In: KDD, p. 3173.
- Mancini, F., Coghill, G.M., Lusseau, D., 2019. Quantifying wildlife watchers' preferences to investigate the overlap between recreational and conservation value of natural areas. J. Appl. Ecol. 56 https://doi.org/10.1111/1365-2664.13274.
- Marmot, M., Bell, R., 2019. Social determinants and non-communicable diseases: time for integrated action. BMJ 364, 1251. https://doi.org/10.1136/bmj.1251.
- Marx, V., More, K.R., 2022. Developing scotland's first green health prescription pathway: a one-stop shop for nature-based intervention referrals. Front. Psychol. 13, 817803 https://doi.org/10.3389/fpsyg.2022.817803.
- Mitchell, R., Popham, F., 2008. Effect of exposure to natural environment on health inequalities: an observational population study. Lancet 372, 1655–1660. https://doi. org/10.1016/S0140-6736(08)61689-X.
- Nesbitt, L., Meitner, M.J., Girling, C., Sheppard, S.R.J., Lu, Y., 2019. Who has access to urban vegetation? A spatial analysis of distributional green equity in 10 US cities. Landsc. Urban Plann. 181, 51–79. https://doi.org/10.1016/j. landurbplan 2018 08 007
- Nikolli, A., Girault, C., 2021. L'accès à la nature au prisme de la crise sanitaire, ou le contrôle politique d'un espace de liberté. Cybergeo. https://doi.org/10.4000/ cybergeo.36211.
- O'Connor, R.C., Wetherall, K., Cleare, S., McClelland, H., Melson, A.J., Niedzwiedz, C.L., O'Carroll, R.E., O'Connor, D.B., Platt, S., Scowcroft, E., Watson, B., Zortea, T., Ferguson, E., Robb, K.A., 2021. Mental health and well-being during the COVID-19 pandemic: longitudinal analyses of adults in the UK COVID-19 Mental Health & Wellbeing study. Br. J. Psychiatr. 218, 326–333. https://doi.org/10.1192/ bjp.2020.212.
- OS Open Greenspace. Greenspaces in Urban and Rural Areas | Vector Map Data | Free Download [WWW Document], n.d. URL. https://www.ordnancesurvey.co.uk/bu siness-government/products/open-map-greenspace, accessed 10.5.21.
- Phillips, B.B., Burgess, K., Willis, C., Gaston, K.J., 2022. Monitoring public engagement with nature using Google Trends. People and Nature 4, 1216–1232. https://doi.org/ 10.1002/pan3.10381.
- Plunz, R.A., Zhou, Y., Carrasco Vintimilla, M.I., Mckeown, K., Yu, T., Uguccioni, L., Sutto, M.P., 2019. Twitter sentiment in New York City parks as measure of wellbeing. Landsc. Urban Plann. 189, 235–246. https://doi.org/10.1016/j. landurbplan.2019.04.024.
- Pornet, C., Delpierre, C., Dejardin, O., Grosclaude, P., Launay, L., Guittet, L., Lang, T., Launoy, G., 2012. Construction of an adaptable European transnational ecological deprivation index: the French version. J. Epidemiol. Community Health 66, 982–989. https://doi.org/10.1136/jech-2011-200311.
- Putra, I.G.N.E., Astell-Burt, T., Cliff, D.P., Vella, S.A., Feng, X., 2021. Do physical activity, social interaction, and mental health mediate the association between green space quality and child prosocial behaviour? Urban For. Urban Green. 64, 127264 https:// doi.org/10.1016/j.ufug.2021.127264.
- Raymond, C.M., Giusti, M., Barthel, S., 2018. An embodied perspective on the coproduction of cultural ecosystem services: toward embodied ecosystems. J. Environ. Plann. Manag. 61, 778–799. https://doi.org/10.1080/09640568.2017.1312300.
- Richardson, E.A., Pearce, J., Mitchell, R., Kingham, S., 2013. Role of physical activity in the relationship between urban green space and health. Publ. Health 127, 318–324. https://doi.org/10.1016/j.puhe.2013.01.004.
- Roberts, M.E., Stewart, B.M., Tingley, D., 2019. Stm: an R package for structural topic models. J. Stat. Software 91, 1–40. https://doi.org/10.18637/jss.v091.i02.
- Roe, J.J., Aspinall, P.A., Ward Thompson, C., 2017. Coping with stress in deprived urban neighborhoods: what is the role of green space according to life stage? Front. Psychol. 8.

- Rosol, M., 2010. Public participation in post-fordist urban green space governance: the case of community gardens in Berlin. Int. J. Urban Reg. Res. 34, 548–563. https:// doi.org/10.1111/j.1468-2427.2010.00968.x.
- Shan, X.-Z., 2020. Association between the time patterns of urban green space visitations and visitor characteristics in a high-density, subtropical city. Cities 97, 102562. https://doi.org/10.1016/j.cities.2019.102562.
- Shoari, N., Ezzati, M., Doyle, Y.G., Wolfe, I., Brauer, M., Bennett, J., Fecht, D., 2021. Nowhere to play: available open and green space in greater London schools. J. Urban Health 98, 375–384. https://doi.org/10.1007/s11524-021-00527-0.
- Song, Yimeng, Chen, B., Ho, H.C., Kwan, M.-P., Liu, D., Wang, F., Wang, J., Cai, J., Li, X., Xu, Y., He, Q., Wang, H., Xu, Q., Song, Yongze, 2021. Observed inequality in urban greenspace exposure in China. Environ. Int. 156, 106778 https://doi.org/10.1016/j. envint.2021.106778.
- [WMS] | Offene Daten Berlin [WWW Document], n.d. URL Status-Index, 2019. https:// daten.berlin.de/datensaetze/status-index-2019-wms. accessed 10.5.21.
- Thompson, C.W., Aspinall, P., Montarzino, A., 2008. The childhood factor: adult visits to green places and the significance of childhood experience. Environ. Behav. 40, 111–143. https://doi.org/10.1177/0013916507300119.
- Twohig-Bennett, C., Jones, A., 2018. The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes. Environ. Res. 166, 628–637. https://doi.org/10.1016/j.envres.2018.06.030.
- Urban Green Space, 2021 [WWW Document] URL. https://www.berlin.de/sen/uvk/en /nature-and-green/urban-green-space/. accessed 10.5.21.
- Venter, Z.S., Barton, D.N., Gundersen, V., Figari, H., Nowell, M., 2020. Urban nature in a time of crisis: recreational use of green space increases during the COVID-19 outbreak in Oslo, Norway. Environ. Res. Lett. 15, 104075 https://doi.org/10.1088/ 1748-9326/abb396.
- Venter, Z.S., Barton, D.N., Gundersen, V., Figari, H., Nowell, M.S., 2021. Back to nature: Norwegians sustain increased recreational use of urban green space months after the COVID-19 outbreak. Landsc. Urban Plann. 214, 104175 https://doi.org/10.1016/j. landurbplan.2021.104175.
- Verwaltungseinheiten der Berliner Forsten [WFS]. Offene Daten Berlin [WWW Document], n.d. URL. https://daten.berlin.de/datensaetze/verwaltungseinheiten-de r-berliner-forsten-wfs. accessed 3.25.22.
- Ward Thompson, C., Roe, J., Aspinall, P., Mitchell, R., Clow, A., Miller, D., 2012. More green space is linked to less stress in deprived communities: evidence from salivary cortisol patterns. Landsc. Urban Plann. 105, 221–229. https://doi.org/10.1016/j. landurbplan.2011.12.015.
- Wheeler, B.W., Lovell, R., Higgins, S.L., White, M.P., Alcock, I., Osborne, N.J., Husk, K., Sabel, C.E., Depledge, M.H., 2015. Beyond greenspace: an ecological study of population general health and indicators of natural environment type and quality. Int. J. Health Geogr. 14, 17. https://doi.org/10.1186/s12942-015-0009-5.
- Wood, C.J., Polley, M., Barton, J.L., Wicks, C.L., 2022. Therapeutic community gardening as a green social prescription for mental ill-health: impact, barriers, and facilitators from the perspective of multiple stakeholders. Int. J. Environ. Res. Publ. Health 19, 13612. https://doi.org/10.3390/ijerph192013612.
- Zhang, J., Yu, Z., Zhao, B., Sun, R., Vejre, H., 2020. Links between green space and public health: a bibliometric review of global research trends and future prospects from 1901 to 2019. Environ. Res. Lett. 15, 063001 https://doi.org/10.1088/1748-9326/ ab7f64.
- Zhang, L., Zhou, S., Kwan, M.-P., Chen, F., Lin, R., 2018. Impacts of individual daily greenspace exposure on health based on individual activity space and structural equation modeling. Int. J. Environ. Res. Publ. Health 15, 2323. https://doi.org/ 10.3390/ijerph15102323.
- Zhang, Y., Van den Berg, A.E., Van Dijk, T., Weitkamp, G., 2017. Quality over quantity: contribution of urban green space to neighborhood satisfaction. Int. J. Environ. Res. Publ. Health 14, 535. https://doi.org/10.3390/ijerph14050535.
- Publ. Health 14, 535. https://doi.org/10.3390/ijerph14050535.
 Zhu, J., Xu, C., 2021. Sina microblog sentiment in Beijing city parks as measure of demand for urban green space during the COVID-19. Urban For. Urban Green. 58, 126913 https://doi.org/10.1016/j.ufug.2020.126913.