Environment International 180 (2023) 108190

Contents lists available at ScienceDirect

Environment International

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

Full length article

Increased nationwide use of green spaces in Norway during the COVID-19 pandemic

Vidar Sandsaunet Ulset [a,*], Zander Venter [b], Michal Kozák [a], Emma Charlott Andersson Nordbø [c], Tilmann von Soest [a]

[a] *PROMENTA Research Center, Department of Psychology, University of Oslo, P.O. Box 1094 Blindern, 0317 Oslo, Norway*
[b] *Terrestrial Ecology Section, Norwegian Institute for Nature Research, P.O. Box 5685 Torgarden, 7485 Trondheim, Norway*
[c] *Department of Public Health Science, Faculty of Landscape and Society, Norwegian University of Life Sciences, Elizabeth Stephansens v. 15, 1430 Ås, Norway*

ARTICLE INFO

Handling Editor: Xavier Querol

Keywords:
Green space use
COVID-19 pandemic
Recreational mobility
NDVI
Sosioeconomic status

ABSTRACT

In recent years, there has been growing concern about the decline in human green space use and nature-based recreation in Western countries. While some evidence suggests that the COVID-19 pandemic led to increased recreational mobility in urban green spaces, it is unclear whether the pandemic led to nationwide changes in green space use in both densely and less densely populated neighborhoods, as well as whether social inequalities in green space use were reinforced or attenuated by the pandemic. To address these questions, we used daily nationwide aggregated mobility data from more than 2 million cell phone subscribers in 14,331 geographical grids across Norway to examine potential changes in mobility in green spaces as measured by the normalized difference vegetation index (NDVI) during the pandemic. Additionally, we controlled for weather conditions, holiday periods, and neighborhood sociodemographic characteristics. The results from linear mixed model analyses showed a 9.4% increase in recreational visits in the greenest spaces during the pandemic. Notably, this increase was most prominent in neighborhoods of low socioeconomic status (SES) and was observed in both high- and low-population density neighborhoods, although the increase was somewhat stronger in neighborhoods with low population density. Our study findings suggest that the COVID-19 pandemic has played a role in increasing nationwide green space use in Norway and potentially narrowing the gap of green inequalities, thus highlighting the importance of preserving and promoting green spaces as a public health resource, particularly in disadvantaged neighborhoods.

1. Introduction

The onset of the coronavirus pandemic in 2020 caused countries around the world to implement unprecedented social distancing measures to stop the spread of COVID-19. During the COVID-19 crisis, spending time in and nearby nature provided individuals with the opportunity to escape confinement and socialize while avoiding places with a high risk of disease transmission, such as malls, cafés, cinemas, and restaurants. Indeed, some studies have reported an increase in the use of natural spaces during the initial 6 months of the pandemic (Venter et al., 2020; Venter et al., 2021; Bristowe and Heckert, 2023). Previously, information collected from mobile phones on the movements and locations of individuals has been used to track population-level mobility patterns and understand the spread of infectious diseases such as COVID-19 (Hu et al., 2021). However, no studies have thus far used aggregated mobility data to examine whether the COVID-19 pandemic led to nationwide changes in the use of green spaces for recreation, whether social inequalities in access to green space decreased or were exacerbated during the pandemic, or whether there were differences in green space use between densely populated and less densely populated neighborhoods.

Exposure to green spaces promotes well-being, is beneficial for a range of health outcomes (Yang et al., 2021; Browning et al., 2022), and, thus, plays an important role in achieving the UN sustainability goal of good health and well-being for all. Green spaces provide social meeting places and are beneficial for health and well-being because they provide opportunities for physical activity, attention restoration, and stress reduction (Markevych et al., 2017; Remme et al., 2021). Moreover, the

---

* Corresponding author.
E-mail addresses: vidar.ulset@psykologi.uio.no (V.S. Ulset), zander.venter@nina.no (Z. Venter), michal.kozak@psykologi.uio.no (M. Kozák), emma.charlott.andersson.nordbo@nmbu.no (E.C.A. Nordbø), t.v.soest@psykologi.uio.no (T. von Soest).

https://doi.org/10.1016/j.envint.2023.108190
Received 19 June 2023; Received in revised form 17 August 2023; Accepted 5 September 2023

presence of green spaces mitigates air pollution, cools the air temperatures, and reduces ambient noise in the environment (Diener and Mudu, 2021; Paull et al., 2020).

Nonetheless, over the past decades, there have been signs of a general reduction in people's exposure to nature. For example, evidence suggests that young people spend less time outdoors in green spaces than previously and, instead, devote more time to electronic media (Hofferth, 2009; Reid Chassiakos et al., 2016; Larson et al., 2018). Moreover, there is evidence of declines in national park visits in countries such as the U. S., Japan, and Spain, as well as reductions in engagement in outdoor camping and time spent hiking outdoors (Pergams and Zaradic, 2008). However, the COVID-19 pandemic led to drastic lifestyle changes all around the world due to the associated curtailment of public mobility (Musselwhite et al., 2020). Indeed, during the COVID-19 lockdowns, green spaces provided safe places for outdoor activity, as they allowed people to maintain a sufficient distance between themselves to avoid disease transmission. In fact, Venter and colleagues reported an approximately 300% increase in outdoor recreation activity during the pandemic lockdown in urban areas of Norway (Venter et al., 2020; Venter et al., 2021). However, these studies were restricted to Oslo, the capital of Norway, and relied on crowdsourced mobility data from the Strava fitness app, which is biased toward the inclusion of middle-aged, socio-economically advantaged, and physically active population groups (Venter et al., 2023).

Aside from changes in green space use over time, there is evidence from before the pandemic of social inequalities in exposure to nature; specifically, neighborhoods with low socioeconomic status (SES) had less proximity to green spaces compared to those with high SES (Rigolon et al., 2018). It is also known that people with low SES experience more mobility restrictions (Bessell, 2022). For example, mobility constrictions are more severe in areas with economic inequalities (Bonaccorsi et al., 2020), among people with low education and income (Chen et al., 2022; Wang and Tang, 2020), and among ethnic minorities (Mackey et al., 2021; Yancy, 2020). However, research on how social inequalities in the nationwide use of green spaces might have changed with the pandemic is currently lacking.

On the one hand, larger burden of restrictions, lack of access to greenspace, limited resources and a dependence on public transport may have led to less recreational greenspace exposure during the pandemic among those living in less affluent neighborhoods. On the other hand, increased use of home office across all socioeconomic strata may have evened out socioeconomic differences in greenspace use by introducing more flexibility for people in low SES neighborhoods to engage in nature-based recreation. However, very little is known about how the pandemic may have influenced such inequalities in exposure to greenspaces.

There may also be differences between densely populated and not so densely populated neighborhoods with respect to use of greenspace, and changes in use of greenspace during the pandemic. In Norway, built-up areas account for only 1.7% of the land cover, with the remaining land being dominated by forests and mountain ecosystems, which are ideal for outdoor recreation (Statistics Norway, 2022). Therefore, even though more than 80% of Norwegians live in densely populated areas, most people have nature close to where they live. However, people living in rural neighborhoods with vast space surrounding them may have been less affected by mobility restrictions than those living in densely populated neighborhoods, meaning the changes in green space use in rural areas during the pandemic may be smaller than the changes observed in densely populated neighborhoods.

During the pandemic in Norway, residents were allowed to spend time outdoors if following restrictions on social distancing. The first lockdown in Norway was announced on March 12th, 2020, during which schools, kindergartens, fitness centers, hair salons, restaurants, and similar public spaces were closed, and cultural events and sports gatherings were banned. As of March 13, 2020, a ban on visits to Norway through Norwegian airports was enforced, with exceptions for citizens returning home. Furthermore, healthcare professionals working with patients were prohibited from leaving the country, and leisure travel was strongly discouraged for all citizens. However, public transport schedules continued as normal. During the summer of 2020, the restrictions were somewhat eased, but all the restrictions were lifted for the first time on September 21st, 2021. As shown in Fig. 1A, there was a sharp increase in the stringency index for the national-level restrictions in March 2020, and this level of restriction was sustained during the study period from January 2019 to November 2021 (with a maximum restriction stringency score of 80). The most prominent increase in the number of new COVID-19 cases occurred during the fall of 2020, and this number reached a peak during the fall of 2021, with 2,485 new cases of COVID-19 per 100,000 inhabitants recorded in one day.

We therefore ask: Did the COVID-19 pandemic and associated social distancing measures result in increased usage of greenspaces, and if so, did such changes vary by neighborhood socioeconomic characteristics and population density? Considering the above research, we hypothesize that 1) the number of dwells (i.e., visits) in green spaces may have increased during the COVID-19 lockdown compared to the previous year, even after controlling for the possible confounding effects of weather conditions, neighborhood population density, neighborhood SES, and public and school holidays. Moreover, we hypothesize that 2) social inequalities in the use of green space may have increased during the COVID-19 pandemic, with a lesser increase in green space exposure in neighborhoods characterized by low education, low household income, and a larger proportion of immigrants. Finally, we hypothesize that 3) changes in mobility in green space during the pandemic may have been more pronounced in urban areas compared to rural areas.

We used daily aggregated mobile tracking data from more than 2 million cell phone subscribers in 14,331 geographical grids across Norway, population registry data on sociodemographic factors, and remote sensing (Normalized Difference Vegetation Index) to examine whether the onset of the COVID-19 pandemic and the associated restriction policies affected the nationwide recreational use of green spaces.

2. Methods

2.1. Study area and data structure

Norway is a country in North-Western Europe with a population of about 5.5 million people, of which 82.4% live in densely populated areas. Norway has a total land area of 323,782 km^2, of which 1.7% is built-up areas and 3.5% is agricultural land. The remaining land area is covered by forests (37.6%), grassland/heathland (37.4%), bare rock (7.4%), inland waters (6.2%), wetland (5.3%), and permanent snow and glaciers (0.8%) (Statistics Norway, 2022). Norway is geographically divided into 356 municipalities and 1,550 smaller neighborhoods (administrative units that are used by the municipalities and regional authorities for statistical analysis and planning purposes). The neighborhoods were, in turn, subdivided into 14,331 geographical grids ranging from 500 m × 500 m to 64,000 m × 64,000 m. Each neighborhood contained an average of 8.3 grids. Grids with a low frequency of visits, typically in remote areas, were of larger sizes than gids with higher frequencies of visits in order to maintain anonymity of the mobile phone subscribers. The dataset included data for 1036 days ranging from January 1, 2019, to November 1, 2021. Thus, our data included a total of 14,846,916 observations (grid days).

2.2. Daily recreational dwells

We obtained aggregated mobility data regarding daily dwells from the Norwegian telephone company Telia, which has approximately 2 million users. All mobile phones registered to Telia's network were tracked, using signal triangulation to locate the mobile phone in space, and the data were further modeled to represent the whole Norwegian

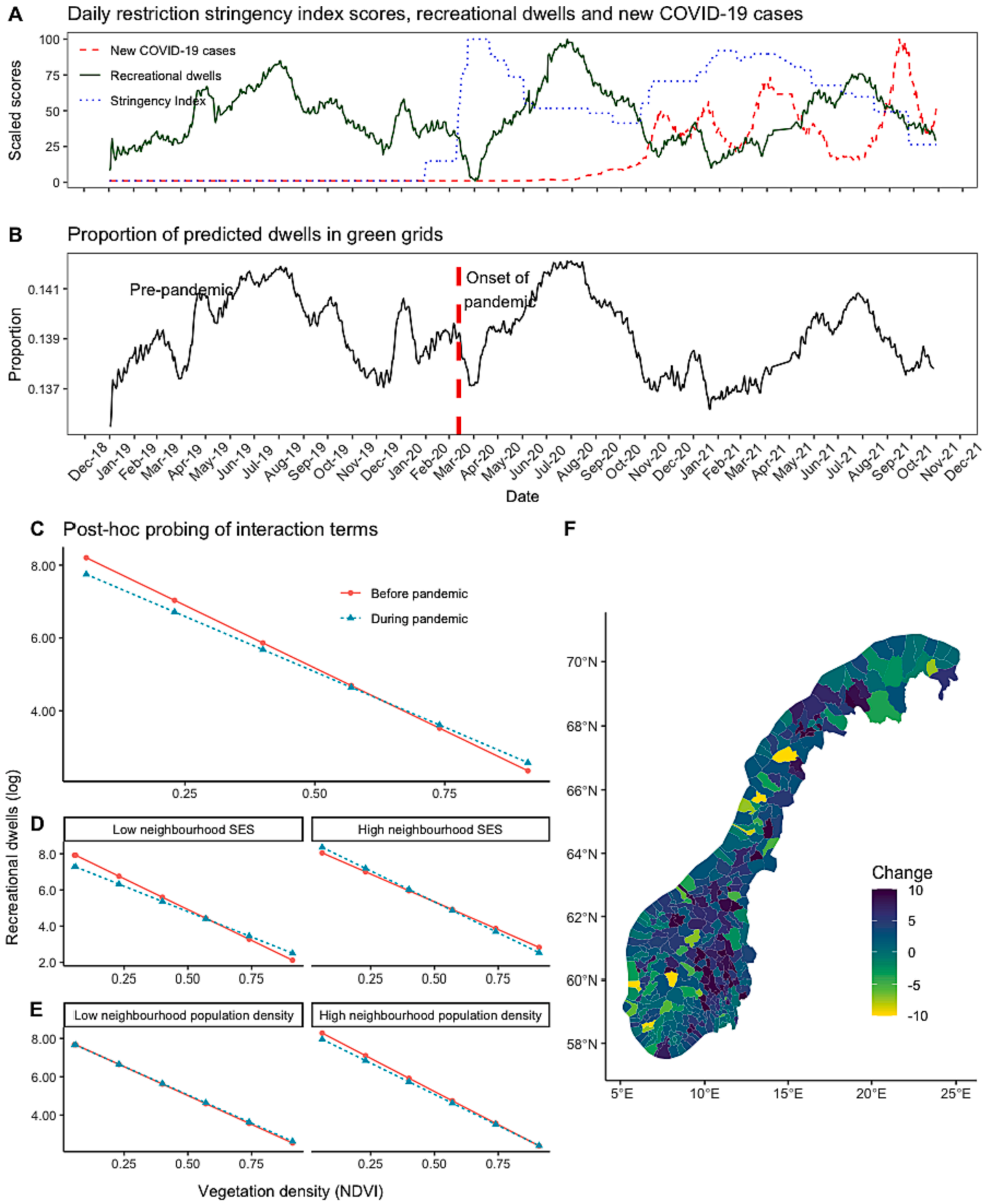

Fig. 1. **A:** Information about COVID-19 infection rates were obtained from the Norwegian Surveillance System for Communicable Diseases. Recreational dwells are raw mobility scores across all grids. Information about national level restriction policies were obtained from the Oxford COVID-19 Government Response Tracker (Gascon et al., 2016). The COVID-19 Stringency Index uses nine metrics (school closures, workplace closures, cancellation of public events, restrictions on public gatherings, closures of public transport, stay-at-home requirements, public information campaigns, restriction on internal movements and international travel controls), and provides daily scores ranging from 0 to 100 (less strict to stricter response). For parsimony, New COVID-19 cases and the Restrictions Stringency Index were scaled from 1 to 100. **B:** The proportion of daily dwells (rolling mean) in green grids was defined as the product of number of model implied predicted dwells and green grids. Green grids was defined with a variable coded 1 to indicate NDVI score above 0.77 (1 SD above the mean), and 0 to indicate NDVI score below 0.77), divided by the total number of dwells. (Daily green dwells $= \frac{\sum \text{Green}^{\text{Grid}}\text{Dwells}^{\text{Grid}}}{\sum \text{Dwells}^{\text{Grid}}}$). **C – E:** Predicted scores of the log transformed number of recreational dwells before and after the pandemic across all levels of vegetation density (NDVI). Low and high neighboorhood SES reflect the minimum and maximum SES scores, respectively. Low and high neighboorhood population density reflect neighboorhoods that fall in to the first and third tertile, respectively. **F:** Change in municipality averages of the number of dwells in green grids (NDVI greater than 0.6). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

population as closely as possible. To maintain anonymity, the mobile company was in control of the data anonymization. Additionally, activity was only registered if there were five or more mobile phone subscribers in a grid within a specified period. Mobility data was generated from both active (e.g. sending an SMS or using data) and passive events (phone stwitches connection from one cell tower to another). In 2020, the average of the daily median time between signals per device was 320.50 s, and the average of the daily median number of signals per device was 237.97 s per day.

For this study, daily interval data from January 1, 2019, to November 1, 2021, were collated, and the "daily recreational dwells" in a grid were defined as the number of mobile phones stationary within a grid cell for at least a 20 min duration per day. If the mobile phone was stationary in a location between 09.00 and 17.00, the dwell was categorized as a work dwell. If the mobile phone was stationary in a location overnight, the dwell was categorized as a home dwell. For this study, all the dwells that were not categorized as either a work or home dwell were categorized as a recreational dwell.

Out of the 14,331 grids, the grid sizes included 500 m × 500 m (28.6 %), 1,000 m × 1,000 m (18.19%), 2,000 m × 2,000 m (16.0%), 4,000 m × 4,000 m (16.5%), 8,000 m × 8,000 m (11.9%), 16,000 m × 16,000 m (3.7%), 32,000 m × 32,000 m (0.69%), and 64,000 m × 64,000 m (0.18%). Overall, the signal quality was good, but on some days, there was a drop in the number of signals compared to the baseline, which could indicate that there were problems with the mobile network infrastructure. This occurred for 13 days in 2019, 14 days in 2020, and 9 days in 2021. However, the drops in network signal were not persistent over time and were spatially random and, thus, did not confound our statistical models.

2.3. Green space

The density of green space was defined using the normalized difference vegetation index (NDVI) (Rhew et al., 2011), which is a widely used remote sensing index that quantifies the normalized difference between visible and near-infrared reflectance and serves as a proxy for vegetation cover. We used data from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Indices (MOD13Q1) Version 6.1 (Didkan, 2021). Data were collected every 16 days at 250 m × 250 m spatial resolution, and the algorithm chose the best available pixel value from the 16 day acquisition period based on the following criteria: low cloud cover, a low view angle, and the highest NDVI value. Since the broader literature shows that that an integrated annual NDVI is a strong proxy for green space exposure (Dadvand et al., 2012; Gascon et al., 2016), we calculated the median scores between January 1, 2019, and January 1, 2020. We used median instead of mean NDVI values because arithmetic means easily provide bias due to outlier NDVI values resulting from cloud contamination (Flood, 2013). The NDVI were aggregated to the mobility data grid by calculating the mean NDVI value within each grid cell.

2.4. Weather data

We gathered ERA–Land Hourly - ECMWF Climate Reanalysis data (Muñoz Sabater, 2019) regarding the snow depth, solar radiation, wind speed, and temperature for each grid with mobility information, and these weather data were collected at daily intervals from January 1, 2019, until November 1, 2021. ERA5-Land is a reanalysis satellite dataset that provides a view of the changes in land variables over several decades at a high resolution.

Specifically, the snow depth was defined as the average snow thickness on the ground (excluding snow on the canopy) in meters. The surface solar radiation was defined as the amount of solar radiation (also known as shortwave radiation) reaching the surface of the Earth in a certain area. Data on this variable were collected at daily intervals, and the units of surface solar radiation are joules per square meter (J m^{-2}). The temperature was defined as the air temperature at 2 m above the surface of the land, sea, or inland waters. The windspeed was defined as the square root of the sum of the squared eastward component of the 10 m wind and the squared northward component of the 10 m wind based on the following equation: windspeed = sqrt([U × U] + [V × V]). The eastward (U component) and northward (V component) wind vector components represent the horizontal speed of the air moving toward the east and north, respectively, at a height of 10 m above the surface of the Earth, and the units of these values are meters per second.

2.5. COVID-19 pandemic- and time-related variables

As an indication of the onset and duration of the COVID-19 pandemic, a dummy variable coded as 0 or 1 was used to indicate, respectively, the pre-lockdown period in Norway (January 1, 2019, to March 11, 2020) and the time after the onset of the first lockdown from March 12, 2020, until November 1, 2021. We also created a dummy variable for school holidays at the municipality level, which was coded as 1 if a date was during a school holiday and coded as 0 if not. Public holidays were also dummy coded in the same way as for school holidays. Seasonal meterological trends in activity were modeled by including dummy variables that were coded as 1 to indicate days that fell within the winter (December, January, February, March), summer (June, July, August), or autumn (September, October, November) seasons. Follow-up analyses modelling seasonal trends with a dummy variable for each calendar month resulted in similar fixed and random effect estimates and p-values.

2.6. Neighborhood socioeconomic status (SES) and population density

Data regarding the neighborhood SES and population density were obtained from Statistics Norway.

Population density. We calculated the neighborhood population density by dividing the neighborhood population by the land area to determine the number of people living in each square kilometer of the neighborhood. Due to the non-normal distribution and right skew of the resulting population density variable, this variable was stratified based on tertiles (Fuertes et al., 2014) into low (<18.2 people/km^2), middle (>18.2 people/km^2 and < 270 people/km^2), and high (>270 people/km^2) population density categories.

SES. Firstly, the proportion of residents in each neighborhood who had completed graduate-level higher education was assessed. Data regarding the educational attainment of the population was collected by examining the proportion of residents aged 16 years or older who had completed their education at an educational institution as of December 31, 2020. Secondly, the median income for households was determined by summing all the monetary income (in Norwegian Kroner [NOK], both taxable and tax-exempt) of the people who lived permanently in the same dwelling as of December 31, 2020. All the amounts were calculated as constant prices based on the previous year's consumer price index. Thirdly, the population proportion of immigrants in a neighborhood was calculated using the number of immigrants and Norwegian-born children to immigrant parents as of December 31, 2020. Immigrants were defined as individuals born abroad to two foreign-born parents and four foreign-born grandparents. In accordance with an already established approach (Pedersen et al., 2015), the education level, median income, and immigrant population proportion were z-standardized and averaged to create a composite neighborhood-level SES variable.

2.7. Analysis

As the hierarchical structure of the data comprised daily observations from geographical grids (grid-days) nested within these geographical grids, which were, in turn, nested within the corresponding neighborhoods, multilevel mixed linear analyses with random intercepts were applied. Grid-level variables regarding the snow depth, surface solar radiation, temperature, and windspeed were included as control variables to control for the possible confounding effects of weather on dwells. The effects of the onset of the pandemic on daily dwells over and above the seasonal trends in weather variables were modeled. To model the effect of the pandemic on activity in green spaces, an interaction term between the COVID-19 pandemic period dummy and NDVI was included in the analysis. To examine differences between rural and urban areas, as well as to examine any social inequalities in the use of green spaces, we specified three-way cross-level interaction terms of NDVI and the COVID-19 pandemic dummy to neighborhood SES and population density. To manage the count data, we used the natural logarithms of the dependent variable in the mixed model analyses. Logarithmic transformation has an additional advantage, as it allows for the interpretation of the estimated effects from dummy variables in terms of percentages (Gelman et al., 2020). All predictor variables were mean centered before they were entered in the multilevel mixed model.

2.8. *Missing data*

Table 1 provides information about completeness of data for each of the variables used in the study. Overall, 6.1 % of the data were missing. Missing data on recreational dwells were due to the anonymization procedure of the mobile company, setting all daily visits in a grid below 5 to missing that day. We were unable to obtain SES data from one of the neighborhoods due to a very low population causing Statistics Norway to anonymize the information by deleting values. We were unable to obtain NDVI and weather data for 2,249 grids that were not covered in the original remote sensing data. Welch’s t-tests showed that grids containing missing data had sligthy less recreational dwells; t (3387999.74) = -19.73, $p < 0.001$. Grids containing missing data on any of the predictor variable had slightly higher SES (t(4435815.16) = 92.79, $p < 0.001$) and population density (t(4428348.62) = 429.68, $p < 0.001$) compared to grids with complete data. Importantly, the pattern of missingness was such that missing values were constant across the entire time series. Missing data were handled by listwise deletion. After incomplete cases were removed, 10,201,513 valid observations in 12,082 grids and 1,459 neighborhoods were used in the multilevel mixed model.

3. Results

Table 1 shows descriptive statistics across the whole study period and before and during the pandemic for all study variables. Daily recreational dwells ranged from 5 to 67,305 across grids, with a mean of 273.70 daily dwells. Fig. 2 shows that across the entire duration of the study, vegetation density (as measured by the NDVI) at the grid level was moderately and negatively correlated with the number of daily recreational dwells, suggesting that there were more daily dwells in areas with low vegetation density compared to areas with high vegetation density. Moreover, there was a moderate negative correlation between the NDVI and population density and a weak positive correlation between the NDVI and neighborhood SES, indicating that densely populated and less affluent areas contained less green space than more affluent areas and areas with lower population density.

Table 2 presents the results from the multilevel mixed model analysis with the number of daily recreational dwells (log transformed) on the grid level as the dependent variable. Model 1 revealed no change in the number of recreational daily dwells after the onset of the pandemic compared to the baseline period before the pandemic. However, when adjusting for the NDVI, neighborhood SES, population density, public holidays, school holidays, season, and weather variables in Model 2, the number of daily recreational dwells decreased by 5% after the onset of the pandemic, thus indicating an overall reduction in daily recreational activity after the pandemic started when controlling for covariates.

In Model 3, we found a positive interaction effect between the COVID dummy variable (coded 0 for the prepandemic period and 1 for the period during the pandemic) and NDVI, suggesting that recreational dwells increased more in grids with higher vegetation density after the onset of the pandemic. Post-hoc probing of the interaction displayed in Fig. 1C indicated that after the onset of the pandemic, there was a 9.44% increase in recreational dwells in the areas with the highest vegetation density (NDVI = 0.91), while there was a 5.54% decrease in recreational dwells in the areas with the lowest vegetation density (NDVI = 0.06). In line with this finding, Fig. 1B demonstrates a sharp increase in the proportion of recreational dwells in green grids that began during the spring of 2020 when the pandemic started.

Table 2, Model 4, shows a significant negative three-way interaction between the COVID dummy, NDVI and neighborhood SES. Post-hoc probing, as shown in Fig. 1D, revealed that during the pandemic, recreational dwells in high-vegetation density, low-SES areas increased by 18.10% (NDVI = 0.91, SES z-score = –1.44), whereas they decreased by 10.35% in high-vegetation density, high-SES neighborhoods (NDVI =

Table 1
Descriptive statistics for variables under study.

					Total		Prepandemic period		Period during the pandemic	
	$n^{grid\ days}$	n^{grids}	n^{nbrhd}	Min - max	Mean	SD	Mean	SD	Mean	SD
Recreational dwells	12,294,957	13,783	1540	5–67,305	273.70	618.43	287.23	728.90	263.63	521.05
Recreational dwells (log)	12,294,957	13,783	1540	1.61–11.12	4.83	1.29	4.83	1.31	4.83	1.27
NDVI	14,846,916	13,850	1540	0.06–0.91	0.66	0.11	0.66	0.11	0.66	0.11
Nbhrd SES	14,348,600	14,327	1539	−1.41–1.44	0	0.31	0.00	0.31	0	0.31
Nbrhd population density	14,842,772	14,331	1540	1–3	2	0.82	2.00	0.82	2	0.82
COVID-19 dummy	14,845,456	14,331	1540	0–1	0.58	0.49	0.00	0.00	1.00	0.00
School holiday dummy	14,846,916	14,331	1540	0–1	0.26	0.44	0.22	0.42	0.28	0.45
Public holiday dummy	14,846,916	14,331	1540	0–1	0.03	0.18	0.03	0.17	0.03	0.18
Winter dummy	14,846,916	14,331	1540	0–1	0.32	0.47	0.44	0.50	0.23	0.42
Spring dummy	14,846,916	14,331	1540	0–1	0.18	0.38	0.14	0.35	0.2	0.4
Summer dummy	14,846,916	14,331	1540	0–1	0.27	0.44	0.21	0.41	0.31	0.46
Autumn dummy	14,846,916	14,331	1540	0–1	0.24	0.42	0.21	0.41	0.26	0.44
Snow depth (meters)	12,212,288	12,616	1460	0–23.08	0.24	0.64	0.28	0.63	0.21	0.64
Solar radiation (J m − 2)	12,212,288	12,616	1460	0–17.80	5.27	4.45	4.34	4.22	5.96	4.49
Temperature (degrees celcius)	12,212,288	12,616	1460	−28.73–26.43	5.57	7.96	4.05	7.65	6.67	8.00
Windspeed (m/s)	12,212,288	12,616	1460	0–20.01	2.34	1.74	2.37	1.78	2.32	1.70

Note. For parsimony, solar radiation values are provided in million joules. The means of the dummy variables can be interpreted as proportions. Nbrhd = neighborhood. NDVI = Normalized Difference Vegetation Index. SES = Socioeconomic status. NDVI, SES and Population density were treated as fixed variables (i.e. it was assumed that they did not change during the study period).

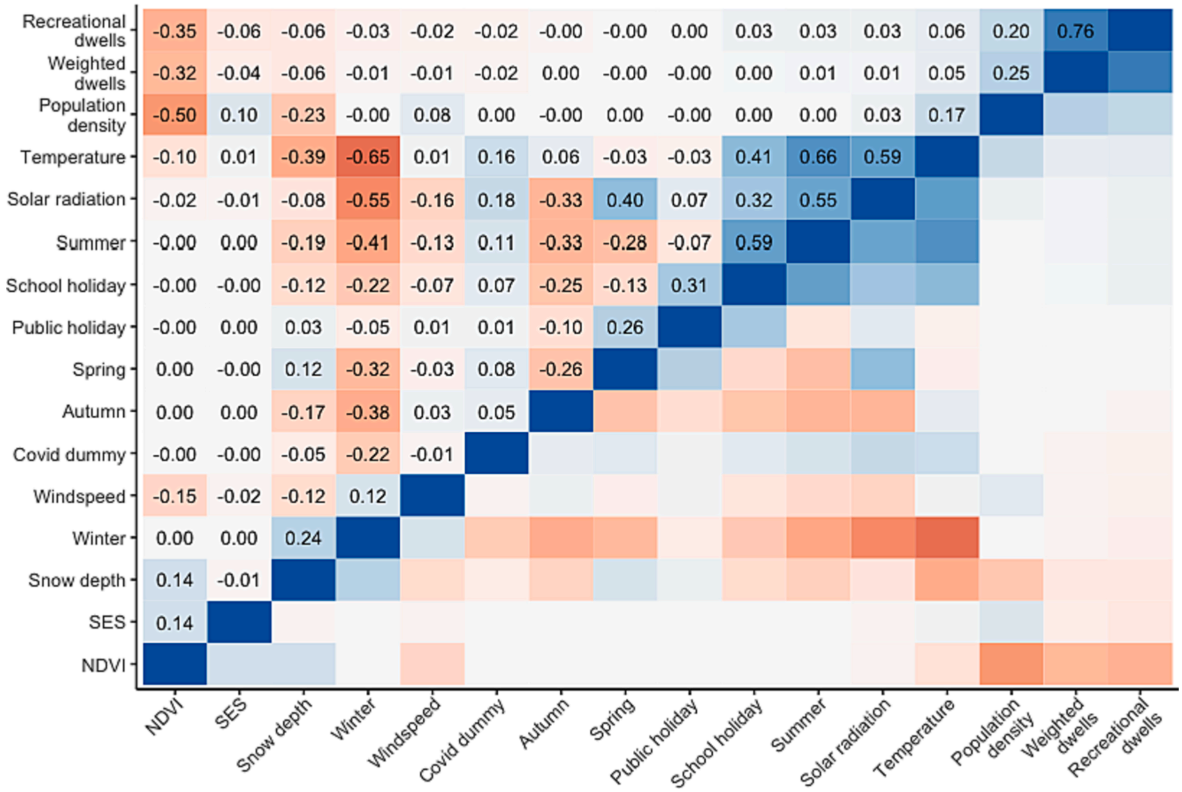

Fig. 2. Pearson's Bivariate Correlations of study variables. *Note.* $p < 0.001$ for all non-zero coefficients. SES = Neighborhood socioeconomic status. NDVI = Normalized Difference Vegetation Index. Weighted dwells = Recreational dwells weigheted by neighborhood population.

0.91, SES z-score = 1.44).

Post-hoc probing of the significant positive three-way interaction between covid dummy, NDVI and population density (Table 2, Model 4) showed a 3.2% increase in recreational dwells in high-vegetation density areas with low population densities (NDVI = 0.91, population density = 18 inhabitants/km^2) and a 0.8% increase in dwells in high-vegetation density areas with high population densities (NDVI = 0.91, population density = 270 inhabitants/km^2). Fig. 1F shows the change in the proportion of recreational dwells in high-vegetation density areas (NDVI greater than 0.6) on the municipality level in all Norwegian municipalities from before to after the onset of the pandemic. The pattern revealed increases in recreational visits to areas where Norwegians typically go to their cabins or summer houses, as well as in the municipalities in northern Norway that are popular tourism destinations (such as Lofoten).

4. Discussion

This study aimed to examine whether daily visits (dwells) to green spaces changed during the COVID-19 pandemic, as well as whether any changes in green space use differed between affluent and less affluent neighborhoods and between densely populated and less densely populated neighborhoods. The results of our study revealed an increase in the proportion of daily recreational dwells in grids with high vegetation density during the pandemic compared to the baseline period of 2019 and 2020 before the pandemic, and this increase was most prominent in neighborhoods with low SES. We also found that the increase in recreational green space use occurred both in neighborhoods with high and low population densities but that the increase was somewhat greater in neighborhoods with low population densities.

Our finding of a substantial increase in the proportion of daily dwells in areas with high vegetation density is consistent with previous research reporting large increases in recreational activity in green spaces in urban areas during the pandemic (Bristowe and Heckert, 2023). Therefore, our study contributes to the existing literature by demonstrating a nationwide relative increase in green space exposure. However, our study also contributes to the existing knowledge base by highlighting the different effects of the pandemic on green space use across urban and rural areas, as well as high-SES and low-SES neighborhoods. Indeed, our findings suggest that the lockdown restrictions led to a considerable decrease in daily dwells in densely populated and low-vegetation density areas.

The COVID-19 pandemic and the associated widespread lockdowns and social distancing measures had an impact on people's daily routines, habits, and psychosocial functioning. Indeed, as indoor recreational facilities closed, many people likely started seeking outdoor activities that would allow them to adhere to social distancing measures while still engaging in leisure pursuits. In this context, green spaces may have provided a safe and accessible place for outdoor activities such as walking, jogging, cycling, and hiking (Labib et al., 2022). Moreover, previous research has shown that the pandemic led to an increase in mental health problems due to social isolation and the disruption of daily routines (von Soest et al., 2022). Since green spaces have been shown to have a positive impact on mental health by reducing stress and increasing social connection (Yang et al., 2021), people may have increasingly turned to green spaces to escape the stresses of the pandemic.

In our study, we found that the positive impact of the pandemic on green space use was most prominent in neighborhoods with low SES. It is known that low-SES neighborhoods were more affected by the negative economic and social impacts of the pandemic (Bessell, 2022; Bonaccorsi et al., 2020). As people living in these areas experienced higher levels of stress, the increased use of green spaces in these neighborhoods during the pandemic may reflect that the green spaces provided opportunities for individuals in those neighborhoods to reduce stress and improve their mental health, social connection, and well-

Table 2
Results from multilevel mixed model analysis.

	Daily recreational dwells (log)			
Fixed effects				
	Model 1	Model 2	Model 3	Model 4
Intercept	4.62^{***}	4.66^{***}	4.66^{***}	4.64^{***}
COVID-19 dummy	0.00^{***}	-0.05^{***}	-0.05^{***}	-0.04^{***}
NDVI		-1.10^{***}	-1.09^{***}	-1.08^{***}
Neighborhood SES		0.16^{**}	0.16^{**}	0.16^{**}
Neighborhood population density		0.02^{***}	0.04^{***}	0.04^{***}
School holiday dummy		0.09^{***}	0.09^{***}	0.08^{***}
Public holiday dummy		0.01^{***}	0.01^{***}	0.01^{***}
Winter dummy		-0.03^{***}	-0.03^{***}	-0.03^{***}
Summer dummy		0.03^{***}	0.03^{***}	0.03^{***}
Autumn dummy		-0.02^{***}	-0.02^{***}	-0.02^{***}
Snow depth (meters)		-0.14^{***}	-0.14^{***}	-0.14^{***}
Solar radiation (J m − 2)		0.09^{***}	0.09^{***}	0.09^{***}
Temperature (degrees celsius)		0.10^{***}	0.10^{***}	0.10^{***}
Windspeed (m/s)		-0.04^{***}	-0.04^{***}	-0.04^{***}
COVID-19 dummy * NDVI			0.14^{***}	0.04^{***}
COVID-19 dummy * NDVI * Neighborhood SES				-0.11^{***}
COVID-19 dummy * NDVI * Neighboorhood population density				0.04^{***}
Random Effects				
σ^2	0.29	0.27	0.27	0.27
τ_{00} grid	1.27	1.18	1.18	1.18
τ_{00} neighborhood	0.51	0.24	0.24	0.24
ICC	0.86	0.84	0.84	0.84
N grid	12,082	12,082	12,082	12,082
N neighborhood	1459	1459	1459	1459
Observations	10,201,513	10,201,513	10,201,513	10,201,513
Marginal R^2 / Conditional R^2	0.000 / 0.860	0.165 / 0.867	0.168 / 0.868	0.169 / 0.868

Note. NDVI = Normalized Difference Vegetation Index. SES = Socioeconomic status.
* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

being.

Concerning social inequities in green space use, our study revealed that the highest-SES neighborhoods displayed nearly equal green space and non-green space usage rates. In contrast, low SES neighborhoods had significantly more dwells in non-green areas and fewer dwells in the greenest areas. This social difference in green space use was evident both before and during the pandemic, but the difference declined slightly during the pandemic as compared to before the pandemic. This suggests that the pandemic may have had a positive effect on green space equity by somewhat reducing the gap in green space access between high-SES and low-SES neighborhoods. This finding contrasts with cross-sectional surveys conducted in other countries that have shown high SES to be a predictor of increased greenspace use during the pandemic (Bristowe and Heckert, 2023; Burnett et al., 2022). The inconsistency between our study's findings and those of other studies could be due to Norway's egalitarian society and strong social welfare system, which likely helped the low-SES neighborhoods cope better during the pandemic. Additionally, Norway's high level of green space availability and cultural emphasis on outdoor activities and nature may have contributed to the increased green space use across all socioeconomic groups during the pandemic and the reduction in the disparities between high-SES and low-SES neighborhoods.

Our study also showed that the COVID-19 pandemic was related to increased green space use in neighborhoods with both high and low population densities, although the increase was most prominent in sparsely populated neighborhoods. Low-population density neighborhoods are likely to have more ample green spaces available, which could explain the more notable increase in green space use in these areas during the pandemic. In contrast, people in neighborhoods with high population densities may face difficulties in practicing physical distancing even within the green areas available to them. As a result, the residents of densely populated areas may have opted to prioritize greenspaces over non-green public spaces for leisure activities to a lesser degree.

Notably, in neighborhoods with high population densities and low SES, we observed a more substantial decline in the number of visits to non-green areas. This finding is consistent with previous research showing greater mobility contraction in urban areas and in areas with lower income per capita (Bonaccorsi et al., 2020). The overall decline in mobility during the pandemic may have been more pronounced in urban areas and low-SES neighborhoods due to the higher risk of transmission and reduced opportunities for leisure activities in these areas, respectively. For example, in non-green areas, such as shopping centers or restaurants, may have been closed or operated with reduced hours during the pandemic, thus reducing the opportunities for leisure activities outside of the home in densely populated neighborhoods. Moreover, low-SES neighborhoods may have fewer opportunities for remote work, meaning that during the pandemic, the residents were required to commute to work, thus reducing their opportunity and mobility to engage in recreational activities. It is also possible that both densely populated and low SES neighborhoods have little green space available, meaning that residents are required to travel outside their neighborhoods to find green spaces and such opportunities for recreation.

This study has several strengths, including the use of nationwide mobility data from more than 2 million cell phone subscribers combined with population registry data, satellite data, and daily weather information to examine the effects of the COVID-19 pandemic on green space use in Norway. Specifically, we used objective measures to identify the number of daily dwells in green spaces and distinguished between different categories of activities such as working, staying at home, and non-home or non-work-related dwells. This methodology allowed us to capture a comprehensive picture of the impact of the pandemic on green space use across different socio-economic and geographic areas in Norway.

However, there are also some limitations in this work that should be acknowledged. Our measure of daily dwells in green spaces did not differentiate between people living in an area and those visiting that area. Therefore, it is possible that some of the increases we observed in green space use were due to an influx of visitors from outside the area rather than an increase in usage by the local residents. To identify recreational dwells, we excluded dwells that were deemed work-related or overnight stays at home. However, we could not conclusively differentiate recreational dwells from other types of mobility, such as shopping or restaurant visits. Therefore, some dwells classified as recreational dwells in this study may have been of a non-recreational nature.

Furthermore, in this study, we utilized the NDVI as a proxy for the amount of accessible green space in an area, but grid cells with a very high NDVI may be inaccessible for recreation use (e.g., train tracks or private properties). The mobility data are short in terms of exact location and purpose of visits. We could not differentiate between mobility within different land cover types if a grid cell contained a mosaic of land cover. Rather, we examined how moility changed within very green versus less green areas. Additionally, the mobility data did not contain demographic information on the individual level, and was likely biased toward middle-aged people and may under-represent children and elderly demographics. Moreover, the mobile company from which the data were obtained uses an algorithm that attaches the location of the mobile device to the nearest housing, which may mean that dwells in very remote wilderness areas may not be accounted for in the dataset. We also focused only on green space but did not consider blue spaces in this work. Indeed, it is likely that people living near open water used such areas for recreation during the pandemic (Korpilo et al., 2021). We also note that our study focused only on Norway, and it is possible that the results may not be generalizable to other countries or regions with different cultural, socio-economic, and geographical characteristics.

Despite these limitations, the findings of this study have several implications for public health and urban planning. Firstly, the observed increase in green space use during the pandemic highlights the importance of access to green spaces for promoting physical activity, mental health, social connection, and overall well-being. Increasing access to and use of green space is particularly important in densely populated urban areas and areas with low socio-economic status, where access to greenspaces is limited. Furthermore, the study highlights the need for enhancing the equitable distribution of greenspaces across different socio-economic and geographic areas. The social inequity in green space use observed in this study suggests that efforts are needed to ensure that all communities have access to high-quality greenspaces that are safe, accessible, and well-maintained. Finally, the study underscores the need for ongoing monitoring and evaluation of green space use to inform evidence-based urban planning and public health policies. Indeed, such planning and policy-making could involve the use of objective measures, such as mobility data, to assess the impact of different interventions on green space use, as well as the collection of data on individual behaviors and attitudes toward green space use.

5. Conclusion

Our study provides important insights into the impact of the COVID-19 pandemic on daily activity in green spaces in Norway and the potential socio-economic and geographic disparities in green space use. Our findings suggest that the pandemic had a significant impact on the use of green spaces, particularly in neighborhoods with low socio-economic status. The observed increase in green space use during the pandemic underscores the importance of access to green spaces for promoting physical activity, mental health, and overall well-being. However, our study also highlights the need for enhancing the equitable distribution of greenspaces and the ongoing monitoring and evaluation of green space use to inform evidence-based urban planning and public health policies.

Funding

This work was supported by the Research Council of Norway [grant number 300816 and grant number 288083].

CRediT authorship contribution statement

Vidar Sandsaunet Ulset: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization. **Zander Venter:** Conceptualization, Formal analysis, Data curation, Writing – review & editing, Resources. **Michal Kozák:** Conceptualization, Writing – review & editing, Resources. **Emma Charlott Andersson Nordbø:** . **Tilmann von Soest:** Supervision, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

References

Bessell, S., 2022. The impacts of COVID-19 on children in Australia: deepening poverty and inequality. Children's Geographies. 20 (4), 448–458.

Bonaccorsi, G., Pierri, F., Cinelli, M., Flori, A., Galeazzi, A., Porcelli, F., Schmidt, A.L., Valensise, C.M., Scala, A., Quattrociocchi, W., Pammolli, F., 2020. Economic and social consequences of human mobility restrictions under COVID-19. PNAS 117 (27), 15530–15535.

Bristowe, A., Heckert, M., 2023. How the COVID-19 pandemic changed patterns of green infrastructure use: A scoping review. Urban For. Urban Green. 81, 127848.

Browning, M.H.E.M., Rigolon, A., McAnirlin, O., Yoon, H.(., 2022. Where greenspace matters most: A systematic review of urbanicity, greenspace, and physical health. Landsc. Urban Plan. 217, 104233.

Burnett, H., Olsen, J.R., Mitchell, R., 2022. Green Space Visits and Barriers to Visiting during the COVID-19 Pandemic: A Three-Wave Nationally Representative Cross-Sectional Study of UK Adults. Land [Internet]. 11 (4), 503.

Chen, Y.-H., Matthay, E.C., Chen, R., DeVost, M.A., Duchowny, K.A., Riley, A.R., Bibbins-Domingo, K., Glymour, M.M., 2022. Excess Mortality in California by Education During the COVID-19 Pandemic. Am. J. Prev. Med. 63 (5), 827–836.

Dadvand, P., Sunyer, J., Basagaña, X., Ballester, F., Lertxundi, A., Fernández-Somoano, A., Estarlich, M., García-Esteban, R., Mendez, M.A., Nieuwenhuijsen, M.J., 2012. Surrounding greenness and pregnancy outcomes in four Spanish birth cohorts. Environ. Health Perspect. 120 (10), 1481–1487.

Didkan, K., 2021. MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V061. NASA EOSDIS Land Processes DAAC.

Diener, A., Mudu, P., 2021. How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective - with implications for urban planning. Sci. Total Environ. 796, 148605.

Flood, N., 2013. Seasonal Composite Landsat TM/ETM+ Images Using the Medoid (a Multi-Dimensional Median). Remote Sensing [Internet] 5(12):[6481-500 pp.].

Fuertes, E., Markevych, I., von Berg, A., Bauer, C.-P., Berdel, D., Koletzko, S., Sugiri, D., Heinrich, J., 2014. Greenness and allergies: evidence of differential associations in two areas in Germany. J. Epidemiol. Community Health 68 (8), 787–790.

Gascon, M., Cirach, M., Martínez, D., Dadvand, P., Valentín, A., Plasència, A., Nieuwenhuijsen, 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.

Gelman, A., Hill, J., Vehtari, A. (Eds.), 2020. Regression and Other Stories. Cambridge University Press.

Hofferth, S.L., 2009. Changes in American children's time - 1997 to 2003. Electron Int J Time Use Res. 6 (1), 26–47.

Hu, T., Wang, S., She, B., Zhang, M., Huang, X., Cui, Y., Khuri, J., Hu, Y., Fu, X., Wang, X., Wang, P., Zhu, X., Bao, S., Guan, W., Li, Z., 2021. Human mobility data in the COVID-19 pandemic: characteristics, applications, and challenges. Int. J. Digital Earth 14 (9), 1126–1147.

Korpilo, S., Kajosaari, A., Rinne, T., Hasanzadeh, K., Raymond, C.M., Kyttä, M., 2021;. Coping With Crisis: Green Space Use in Helsinki Before and During the COVID-19 Pandemic. Frontiers in Sustainable. Cities 3.

Labib, S.M., Browning, M.H.E.M., Rigolon, A., Helbich, M., James, P., 2022. Nature's contributions in coping with a pandemic in the 21st century: A narrative review of evidence during COVID-19. Sci. Total Environ. 833, 155095.

Larson, L.R., Szczytko, R., Bowers, E.P., Stephens, L.E., Stevenson, K.T., Floyd, M.F., 2018. Outdoor Time, Screen Time, and Connection to Nature: Troubling Trends Among Rural Youth? Environ. Behav. 51 (8), 966–991.

Mackey, K., Ayers, C.K., Kondo, K.K., Saha, S., Advani, S.M., Young, S., Spencer, H., Rusek, M., Anderson, J., Veazie, S., Smith, M., Kansagara, D., 2021. Racial and Ethnic Disparities in COVID-19–Related Infections, Hospitalizations, and Deaths. Ann. Intern. Med. 174 (3), 362–373.

Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., de Vries, S., Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J., Lupp, G., Richardson, E.A., Astell-Burt, T., Dimitrova, D., Feng, X., Sadeh, M., Standl, M., Heinrich, J., Fuertes, E., 2017. Exploring pathways linking greenspace to health: Theoretical and methodological guidance. Environ. Res. 158, 301–317.

Muñoz Sabater, J., 2019. ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Musselwhite, C., Avineri, E., Susilo, Y., 2020. Editorial JTH 16 -The Coronavirus Disease COVID-19 and implications for transport and health. J. Transp. Health 16, 100853.

Paull, N., Krix, D., Torpy, F., Irga, P., 2020. Can Green Walls Reduce Outdoor Ambient Particulate Matter, Noise Pollution and Temperature? Int. J. Environ. Res. Public Health 17 (14), 5084.

Pedersen, W., Bakken, A., von Soest, T., 2015. Adolescents from affluent city districts drink more alcohol than others. Addiction 110 (10), 1595–1604.

Pergams, O.R.W., Zaradic, P.A., 2008. Evidence for a fundamental and pervasive shift away from nature-based recreation. PNAS 105 (7), 2295–2300.

Reid Chassiakos, Y., Radesky, J., Christakis, D., Moreno, M.A., Cross, C., Council On C, et al., 2016. Children and Adolescents and Digital Media. Pediatrics 138(5): e20162593.

Remme, R.P., Frumkin, H., Guerry, A.D., King, A.C., Mandle, L., Sarabu, C., Bratman, G. N., Giles-Corti, B., Hamel, P., Han, B., Hicks, J.L., James, P., Lawler, J.J., Lindahl, T., Liu, H., Lu, Y.i., Oosterbroek, B., Paudel, B., Sallis, J.F., Schipperijn, J., Sosič, R., de Vries, S., Wheeler, B.W., Wood, S.A., Wu, T., Daily, G.C., 2021. An ecosystem service perspective on urban nature, physical activity, and health. PNAS 118 (22).

Rhew, I.C., Vander Stoep, A., Kearney, A., Smith, N.L., Dunbar, M.D., 2011. Validation of the normalized difference vegetation index as a measure of neighborhood greenness. Ann. Epidemiol. 21 (12), 946–952.

Rigolon, A., Browning, M., Lee, K., Shin, S., 2018. Access to Urban Green Space in Cities of the Global South: A Systematic Literature Review. Urban Science [Internet]. 2 (3), 67.

Statistics Norway. Land use and land cover 2022 [Available from: https://www.ssb.no/en/natur-og-miljo/areal/statistikk/arealbruk-og-arealressurser].

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 (10), 104075.

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 Plan. 214, 104175.

Venter, Z.S., Gundersen, V., Scott, S.L., Barton, D.N., 2023. Bias and precision of crowdsourced recreational activity data from Strava. Landsc. Urban Plan. 232, 104686.

von Soest, T., Kozák, M., Rodríguez-Cano, R., Fluit, D.H., Cortés-García, L., Ulset, V.S., Haghish, E.F., Bakken, A., 2022. Adolescents' psychosocial well-being one year after the outbreak of the COVID-19 pandemic in Norway. Nat. Hum. Behav. 6 (2), 217–228.

Wang, Z., Tang, K., 2020. Combating COVID-19: health equity matters. Nat. Med. 26 (4), 458.

Yancy, C.W., 2020. COVID-19 and African Americans. J. Am. Med. Assoc. 323 (19), 1891–1892.

Yang, B.-Y., Zhao, T., Hu, L.-X., Browning, M.H.E.M., Heinrich, J., Dharmage, S.C., Jalaludin, B., Knibbs, L.D., Liu, X.-X., Luo, Y.-N., James, P., Li, S., Huang, W.-Z., Chen, G., Zeng, X.-W., Hu, L.-W., Yu, Y., Dong, G.-H., 2021. Greenspace and human health: An umbrella review. The. Innovation. 2 (4), 100164.