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A dataset of acoustic measurements from soundscapes collected worldwide during the COVID-19 pandemic

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Political responses to the COVID-19 pandemic led to changes in city soundscapes around the globe. From March to October 2020, a consortium of 261 contributors from 35 countries brought together by the Silent Cities project built a unique soundscape recordings collection to report on local acoustic changes in urban areas. We present this collection here, along with metadata including observational descriptions of the local areas from the contributors, open-source environmental data, open-source confinement levels and calculation of acoustic descriptors. We performed a technical validation of the dataset using statistical models run on a subset of manually annotated soundscapes. Results confirmed the large-scale usability of ecoacoustic indices and automatic sound event recognition in the Silent Cities soundscape collection. We expect this dataset to be useful for research in the multidisciplinary field of environmental sciences.

Background & Summary

In response to the rapid spread of the coronavirus disease 2019 (COVID-19) around the world, governments of many countries adopted physical distancing measures in early 2020, including more or less drastically restricting individual travel and suspending many work and leisure activities deemed 'non-essential'[1–3]. Incidentally, these public health policy decisions opened a window of opportunity for many environmental scientists to investigate the effects of such a reduction in human activity on ecosystems at multiple spatiotemporal scales[4–8].

The modification of soundscapes, especially in urban and peri-urban areas, was among the most significant environmental changes observed during this period[9–14]. The sudden decrease in individual travel and motorized transport of people and goods shaped extraordinary soundscapes in most cities of the world for a few weeks. This revealed the richness of animal sounds in urban areas, previously hidden by a multitude of anthropogenic sounds. Such a change, directly perceptible by the population, even raised interest outside the academic sphere, as reflected in numerous articles in the general press. Among the thousands of press articles on the subject, we will particularly mention the interactive publications produced by *The New York Times* (see, for example: The Coronavirus Quieted City Noise. Listen to What's Left; or: The New York City of Our Imagination).

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From an academic point of view, several studies have already been carried out on these "soundscapes of a confined world", at different scales and in different types of spaces and territories (sub-continents[15], countries[16–21], regions[22–25], cities[18,26–33], neighborhoods[29,34], protected natural areas[35], semi-anthropized environments[36–38], tourist sites[39]). Among these studies, some benefited from sensor networks predating the COVID-19 crisis, mobilizing for example underwater acoustics and/or seismic monitoring networks[16,22,40], permanent noise pollution monitoring networks in urban environments[26,41,42], or devices installed for pre-existing research projects[43]. Beyond these physical measurement approaches, several studies have also investigated individual and subjective perceptions of changes in soundscape composition. More specifically, the perceived proportion between natural and anthropogenic events in the soundscape is regularly raised in investigations that more broadly address the changes induced by different periods of population containment on experiential relationships to nature[21,29,44].

In this paper, we present a global acoustic dataset[45], collected between March and October 2020 by 261 contributors, at 317 sites distributed in 35 countries (Fig. 1). Recordings were primarily collected using Open Acoustic Devices AudioMoth[46] or Wildlife Acoustics Song Meters SM4 (www.wildlifeacoustics.com) programmable recorders, which are widely used within the professional and amateur naturalist communities. This dataset is unique, with its international dimension, collaborative construction and open access availability. The acoustic data are presented in addition to climate classification and surrounding environment, offering a more comprehensive understanding of their significance and implications. In addition, we provide a set of descriptors based on ecoacoustic indices[47] and on automatic recognition of sound categories using a pretrained deep neural network[48]. These descriptors were subsequently validated by collecting expert annotations on a small subset of the dataset, with which we derived statistical models to demonstrate their usability.

Methods

Silent Cities is a data collection that involved programmable audio recordings worldwide. The global scale of the project warranted us to not only gather acoustical recordings, but also contextualize them. We first describe the data collection procedures, the contributors' network and contextual information related to the recording sites, such as location, urban density, climate classification or governmental policies related to human population containment in response to COVID-19. Next, we describe the processing of acoustic measurements computed on all recordings, including ecoacoustic indices, automatic sound event recognition, and voice activity detection.

Data collection.

Recording protocol. On March 16, 2020, the French government announced the upcoming first containment of the population. A few days later, a first version of the Silent Cities protocol was submitted to professional networks. Feedback from researchers but also from journalists, artists and biological conservation practitioners interested in contributing were received. As requested, a more inclusive version, opening up the possibility of using different equipment and sampling efforts while preserving requirements for further robust statistical analyses was proposed (https://osf.io/m4vnw/). This second and final version of the protocol was shared on March 25, 2020 and is described below.

Each contributor provided recording equipment. To homogenize the recordings collection, recording devices were configured to obtain a 1 minute-long recording every 10 minutes on a daily cycle schedule, with a sampling rate set at 48 kHz. All recorders were to be set in Coordinated Universal Time (UTC+00) with an output format in .wav. In order to have comparable data, the use of an audible SM4 (Wildlife Acoustics) or an AudioMoth (Open Acoustic Devices), which were the two most popular programmable recorders at the time, was recommended. However, any device with high quality recording, allowing the recording configuration requested, was accepted. To anticipate the return of high levels of anthropogenic sounds after the end of containment measures, the gain was to be set at "low" for the Audiomoth and at 31 dB for the SM4 (gain at 5 dB and preamplification at 26 dB). The final dataset includes 216 sites monitored by an Audiomoth, 47 by an SM4 and 54 by another device.

The sampling duration of the collection was locally dependent. The protocol recommended to continue recording a minimum of two weeks after the end of the total city shut down and restoration of "normal" activities. However, the expected scenario of the return to "normal" activity extended well beyond predictions as the magnitude of the pandemic became progressively realised. As containment measures were being lifted in many countries during the summer, the acoustic sampling was ended on July 31, allowing contributors to continue collecting data after this date based on local situations. To summarise, the entire recordings collection covers the period from March 16 to October 31, 2020, with the highest number of recordings between April and July (see Fig. 1d).

Originally, contributors were able to choose between three levels of sampling effort based on their ability to record during the entire or partial duration of the project. Hereafter, we refine the definition of those levels to better fit the diversity of recording profiles represented in the final data set:

- expert - The daily cycle schedule, duration of files and sampling rate were set according to the recommendations, and the duration of the sampling period was at least two months;
- modified - The parameters are set as recommended but the sampling period is less than two months or some parameters such as the file duration, the sampling rate or the daily cycle schedule are different (*i.e.* every 3 hours), while conserving a fixed recording pattern along the sampling period;
- opportunistic - All other sites that do not show any type of recording patterns.

The expert protocol was applied by 228 contributors, while the modified protocol and the opportunistic protocol were followed respectively by 72 and 17 contributors.

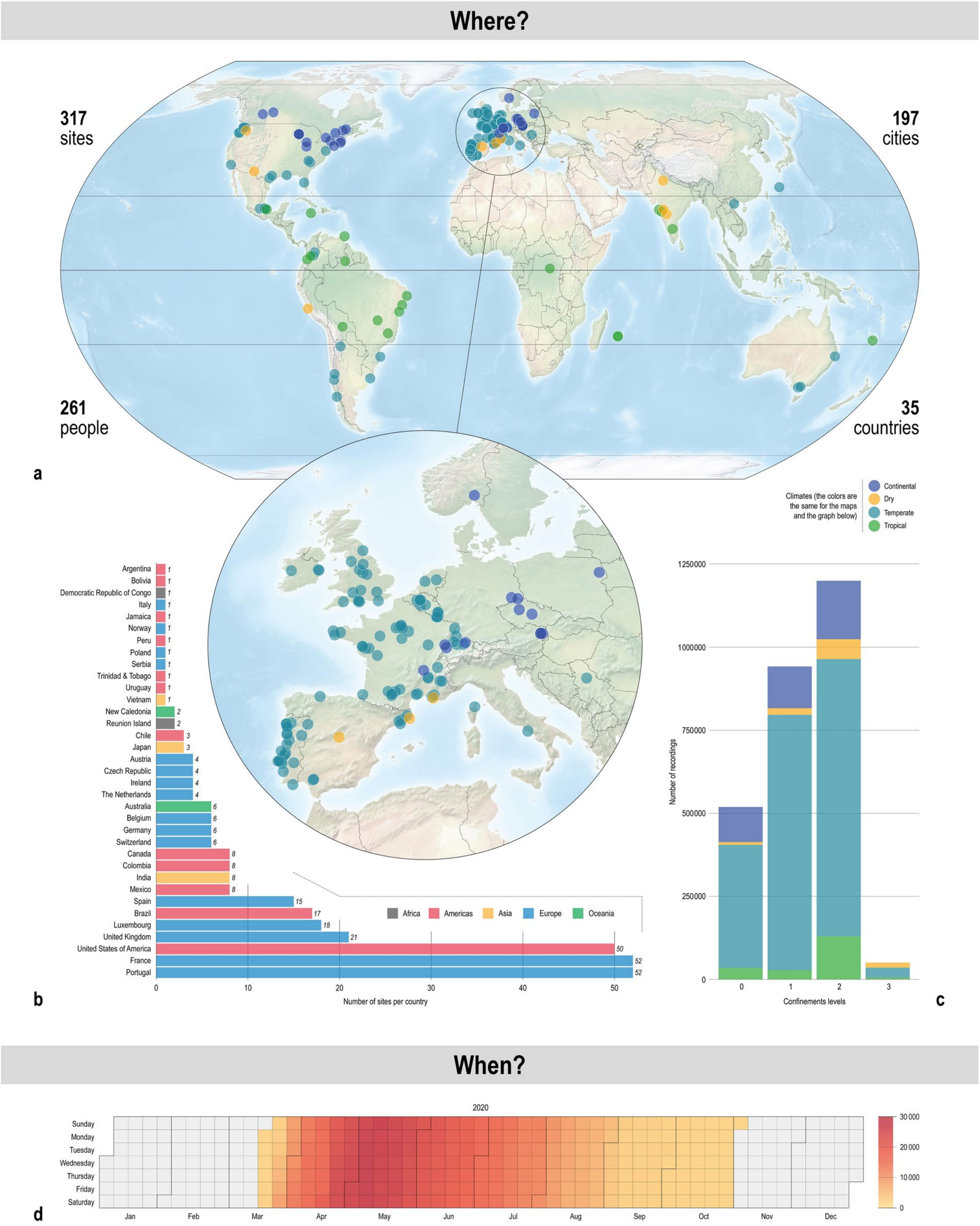

Fig. 1 Panel a. Global and European mapping of recording sites. Colors refer to climates. Panel b. Number of recording sites per country. Colors refer to continents. Panel c. Number of recordings by confinement level and climate. Panel d: temporal distribution of global sampling effort, in number of recordings.

International contributor network. The dataset[45] results from the collaborative work of 261 international contributors from various professional fields: 182 are academics, 37 are conservationist practitioners, 12 are artists and 30 do not recognize themselves in the three previous groups. An Open Science Foundation (OSF) project[45] was created to organize the data collection and guarantee its open access with no restrictions. Other tools used to manage the collaborative work were Framaforms (https://framaforms.org/abc/fr/) to collect metadata about sites and contributors from the consortium.

Site descriptions. The containment of a large number of citizens worldwide restricted the location of the recorders. Contributors deployed their recorder on private land or a balcony at their residency (example on Fig. 2a). We encouraged those living in (peri-)urban areas to participate, even though recordings were also collected in rural areas. The soundscape recordings were collected from 317 sites located in or around 197 cities and 35 countries (see Fig. 1). In order to protect citizens' privacy, the exact coordinates of the sites remain unknown and the location of the sites were based on the coordinates of their corresponding cities and approximate neighborhood. The sites cover four of the five climates defined by the Köppen climate classification[49], with a majority of sites located in the temperate and dry climates and a spatial sampling in favor of the European and American continents (see Fig. 1). For each site, we extracted information about the surrounding land cover (more specifically the percentage of built-up and tree cover within a 1 km radius buffer scale around the sites; 100 m resolution[50]), human footprint (from 0 to 50, with the lowest score depicting the least human influence, 1 km resolution[51,52]), and population density (no. of inhabitants per square kilometer, 1 km resolution[53]) to document the degree of urbanization and human impact on the landscapes encompassing the recordings. In addition, contributors described in a few sentences the surroundings/context of their site. Thanks to the open data available on https://aa.usno.navy.mil/data/AltAz, we also extracted for each recording site the altazimuth coordinates of the Moon and Sun as well as the moon phase for each 10-second time interval during the days where soundscapes were collected. These data would be important for potential analysis about temporal soundscape dynamics. Finally, containment measures[3] per country and date, summarized by the University of Oxford in the *Oxford COVID-19 Government Response Tracker* dataset, were downloaded from the web portal https://ourworldindata.org/grapher/stay-at-home-covid. These stay-at-home requirements are organized in 4 levels:

- 0 - No measures;
- 1 - Recommended not to leave home;
- 2 - Not allowed to leave home, with exceptions for daily exercise, grocery shopping, and other activities considered as essential;
- 3 - Not allowed to leave home, with rare exceptions (*e.g.* allowed to leave only once every few days, or only one person at a time).

Due to the limited data collected during the strictest containment period (level 3, see Fig. 1c), we combined data from the two periods when leaving home was not permitted (levels 2 and 3) when performing the technical validation.

Acoustic measurements.

All computations described here were performed with open-source packages or code from github, including scikit-maad (v1.4)[54,55], librosa[56] and pytorch[57]. The analysis code used to prepare this dataset is available for reference at https://github.com/brain-bzh/SilentCities.

Preprocessing audio. Audio preprocessing was divided into two steps. First, the file name, sample rate, date and relative sound pressure level were extracted from each audio recording. Then, each file (n = 2,701,378) was divided into 10-second segments (n = 16,252,373) in order to have a meaningful duration for both acoustic index calculation and automatic sound event recognition. The sampling rate of audio segments were homogenised at 48 kHz for acoustic index calculation and resampled to 32 kHz for automatic sound event recognition. For acoustic indices, the signals were filtered using a bandpass filter from 100 Hz to 20 kHz to remove low frequency electronic noise inherent to some recorders.

Acoustic Indices calculation. Acoustic diversity indices aim to summarize the overall complexity of an acoustic recording in a single mathematical value. Numerous acoustic indices have been previously proposed[47,58,59], considering the time, frequency and/or amplitude dimensions of the recorded sound wave. We selected and calculated eight indices on all recordings; these indices were chosen based on their complementary and/or wide representation in the literature:

- dB represents the relative acoustic energy of a signal;
- dB Full Scale or dBfs represents the acoustic energy of a signal where the RMS value of a full-scale sine wave is defined as 0 dBfs[60];
- Acoustic Complexity Index or ACI[61] measures the frequency modulation over the time course of the recordings. The value is calculated on a spectrogram (amplitude per frequency per time). ACI is described to be sensitive to highly modulated sounds, such as song birds, and less affected by constant sounds, such as background noise;
- Activity or ACT[62] corresponds to the fraction of values in the noise-reduced decibel envelope that exceed the threshold of 12 dB above the noise level. This noise level was estimated for each site by seeking the audio file yielding the minimum dB value;
- Bioacoustic index or BI[63] measures the area under the frequency spectrum (amplitude per frequency) above a threshold defined as the minimum amplitude value of the spectrum. This threshold represents the limit between what can be considered acoustic activity (above threshold) and what could be considered background noise (under threshold);
- Entropy of the Average Spectrum or EAS[62] is a measure of the 'concentration' of mean energy within the mid-band of the mean-energy spectrum;
- Entropy of the Spectrum of Coefficients of Variation or ECV[62] is derived in a similar manner to EAS except that the spectrum is composed of coefficients of variation, defined as variance divided by the mean of the energy values in each frequency bin;

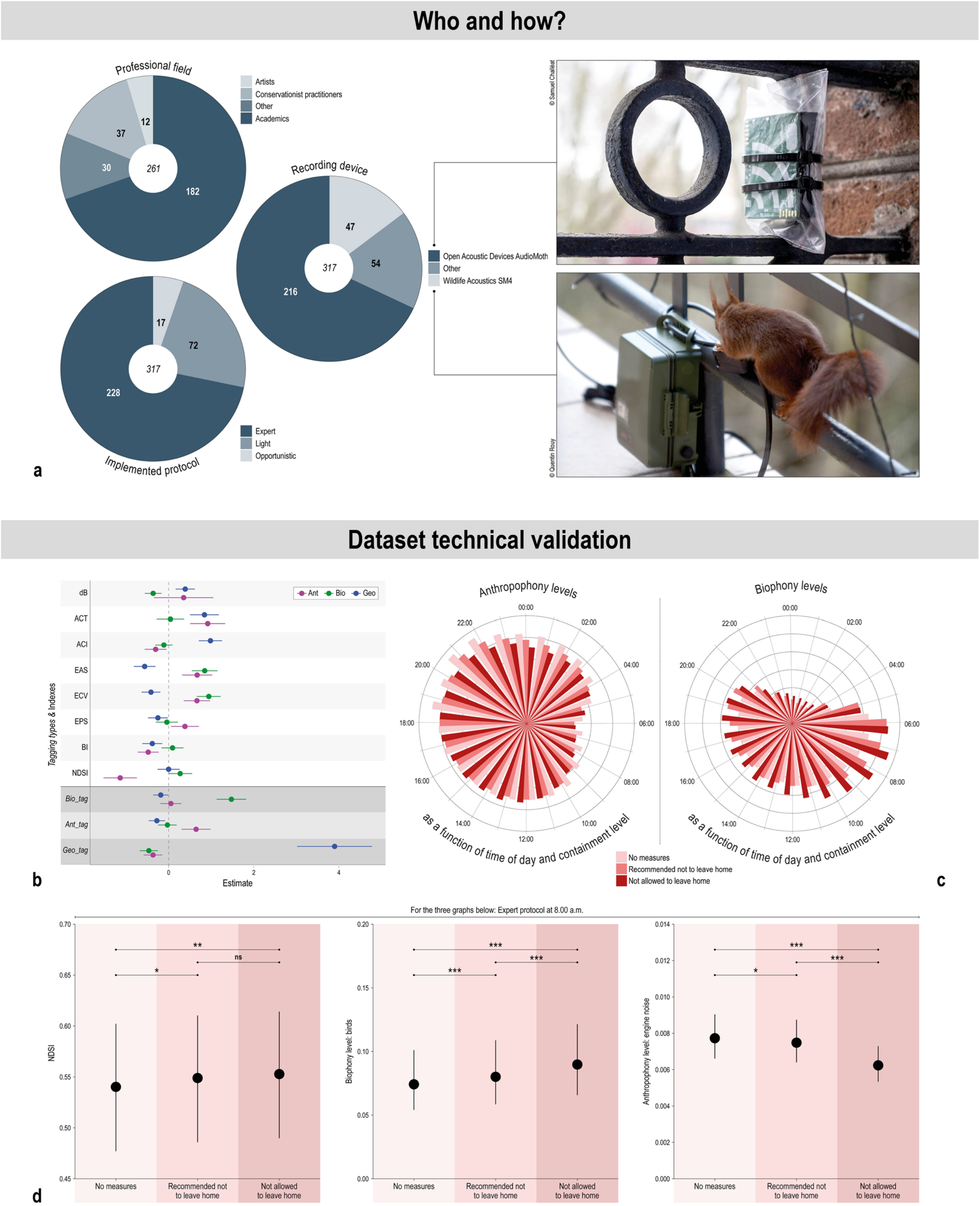

Fig. 2 Panel a. Top left: Professional fields of the 261 participants. Middle: Distribution of type of devices for the 317 recording sites. Bottom left: type of protocol implemented. Right: Photos of the two main recording devices used: Open Acoustic Devices AudioMoth (top) and Wildlife Acoustics SM4 (bottom). Panel b. Association between the measured acoustic indices and tagging types and the presence of geophonical (Geo), biophonical (Bio) and anthropophonical (Ant) events detected manually by the contributors. Model estimates and associated 95% confidence intervals are represented with points and bars, respectively. Positive and negative estimates with confidence intervals not overlapping zero indicate positive and negative associations, respectively. Panel c. Radial barplots depicting the mean anthropophony and biophony level values per site, combining all protocols, recorded hourly throughout each period of COVID-19 containment levels. Panel d. Model predictions and associated 95% confidence intervals for NDSI, biophony (birds) and anthropophony (engine noise) levels at 8:00 a.m. during the COVID-19 confinement measures, following the expert protocol only. ***$p < 0.001$, **$p < 0.010$, *$p < 0.050$, ns: $p > 0.050$.

- Entropy of the Spectral Peaks or EPS[62] is defined as a measure of the evenness or 'flatness' of the maximum-frequency spectrum, maximal frequencies being measured along the time of the recording. A recording with no acoustic activity should show a low EPS value, as all spectral maxima are low and constant over time;
- Normalized Difference Soundscape Index or NDSI[64] measures a ratio between biophony and anthropophony. The value of this index is calculated on a spectrogram and varies between -1, meaning the entire acoustic energy of the recording is concentrated under the frequency threshold of 2kHz and attributed to anthropophony only, and +1, meaning the entire acoustic energy of the recording is concentrated above the frequency threshold and attributed to biophony only.

Manual soundscapes description. In order to have a more thorough description of the recorded soundscapes, some contributors manually performed sound identification on a subset of their recordings. Two non-consecutive days of recordings were randomly selected for each site and each one-minute-long audio file recorded at the beginning of each hour was analysed (*i.e.* a total of 48 1-min files). Using software dedicated to sound analysis (e.g. Audacity: https://www.audacityteam.org/, Sonic visualizer: https://www.sonicvisualiser.org/, and Kaleidoscope: https://www.wildlifeacoustics.com/uploads/user-guides/Kaleidoscope-User-Guide.pdf), contributors were to (i) listen and view spectrograms of the recordings, (ii) estimate the percentage of time occurence (0%, 1-25%, 25-50%, 50-75% and 75-100%) of geophonic, biophonic, and anthropophonic events in each audio file, and (iii) provide more information about the source/type (e.g. geophony: wind, rain and river; biophony: birds, mammals and insects; anthropophony: car, plane and music) of each event. They further indicated the strength/intensity (on a scale from 0 to 3) of the identified geophonic and anthropophonic events and to provide for each biophonic event the number of different song/call/stridulation types visible on the spectrogram. Scoring per recording was associated with a confidence level on a scale from 1 to 5 (see Table 3 for an example of the identification table, inspired from protocol proposed in[65]).

A total of 1351 minutes of sounds were manually described from 30 sites. Contributors from Europe (Austria, Czech Republic, France, Germany, Ireland, Poland, Portugal, Serbia, and United Kingdom), the Americas (Canada, Colombia, Mexico, and United States of America), and Australia participated in the manual sound identification process. The number of audio files described varied slightly between participants (min: 9 minutes, max: 96, median: 48, mean: 45). Most audio files manually analyzed were recorded using AudioMoth (19 sites) and SM4 (8 sites).

Recordings were dominated by geophonic, biophonic and anthropophonic events (*i.e.* time occurence >75% within 1-min files) in 20, 34 and 51% of the 1351 minutes of sounds recorded, respectively. The most detected geophonic sounds were from wind (26% of the total number of records, including 76 records with strong wind intensity) and rain (12%). Bird calls (63%) and insect stridulations (16%) were the most encountered biophonic sounds. Around one third of the recordings with bird calls contained at least four different bird call types. Noise from cars (61%) and people talking (26%) were responsible for most of the anthropophonic sounds.

Automatic sound event recognition. Automatic sound event recognition (SER) became an essential task due to the immense volume (around 20 Terabytes) of the Silent Cities dataset. We adopted the AudioSet ontology and dataset[66], which covers a wide range of everyday sounds. We explored the viability of utilizing PANNs (pretrained audio neural networks) pretrained on the full AudioSet data (available online: https://github.com/qiuqiangkong/audioset_tagging_cnn). The choice of a pretrained model was driven by its generality, as it has been exposed to a wide range of sounds, rendering it suitable for recognizing various audio events. In implementing our methodology, we employ a zero-shot inference approach. This involves applying the pretrained model directly to the entirety of the Silent Cities recordings without the need for additional training or fine-tuning. By doing so, we can benefit from the model's generalization capabilities and avoid the time-consuming process of manual annotation. To categorize the diverse audio events within our dataset, we leverage the Audioset ontology and make necessary adaptations. Specifically, we classify the sounds into three main types: anthropophony (sounds produced by human activities), biophony (sounds originating from natural living organisms), and geophony (sounds resulting from non-living sources like weather or geological activities). The details of sound event grouping (i.e. audio tagging types) and corresponding labels are presented in Table 4 to provide clarity and consistency in the classification process. This grouping was also done to have the same categories than in the manual annotation described in the previous section.

Voice activity detection. As many recordings in Silent Cities were performed at home (e.g. on a balcony) during periods of containment, human voices are likely to be heard and speakers may be easily identified. In order to prevent issues related to privacy, we identified audio segments containing speech and only shared in open access the audio segments without speech. Voice activity detection was conducted using a general purpose voice activity detector (GP-VAD) that was pretrained on noisy, natural speech recordings in the wild[67] (available online: https://github.com/RicherMans/GPV). We applied GP-VAD on a subset of 250000 one-minute recordings (approx. 24 weeks). Detections on this subset were considered as a ground truth speech label, that we set a reference to detect speech in the entirety of the Silent Cities dataset, for which we have a weak speech label from the Audioset SER (described in the previous paragraph). More precisely, we used the GP-VAD predictions on the subset to estimate a receiver-operator characteristic curve, and by setting a true positive rate of detecting 75 % of speech recordings, we obtain an average false positive rate of 34 % false alarms when using the Audioset SER. The corresponding threshold was applied on the raw probability from the Audioset SER on the entirety of the dataset, which eventually resulted in a rejection of 2,868,098 10-second audio segments, representing approximately 18 % of the dataset.

Name	Description	Type	Number of files
Collection of acoustic recordings	Preprocessed 10-second audio files from soundscape recordings collected for each site (compressed in tar.gz archives)	FLAC	16,252,373
Glossary	Definitions of table elements	csv	1
dB	List of readable files uploaded by the contributors and their dB level (archived in a single zip file)	csv	317
Site	Information about each site including contributors' description about the recorder (*e.g.* type and serial number), the location (*e.g.* description of the surrounding area, city), and the description of the containment measures in place at the time of deployment. Also contains the metadata describing the landscape (*e.g.* population density, climate) corresponding to the cities of the dataset as well as the extracted information about the protocol used (*e.g.* type, sampling rate, file duration), and the amount of data collected	csv	1
ConfinementLevels	For each country and date covered by the acoustic collection, displays information about the levels of "stay-at-home requirements" according to the dataset built by the University of Oxford	csv	1
SunMoon	Information about the sun and moon azimuth and altitude for the dates and times covered by the Silent Cities dataset, with a 10-second increment, for each city (197 csv files in a zip file)	csv	197
AcousticMeasurements	List of preprocessed 10-second acoustic files and associated calculations of acoustic indices and categories of automatic sound event (all csv files compressed in a single zip file)	csv	317
AcousticMeasurements_nospeech	Same as AcousticMeasurements but only for recordings without speech (all csv.gz files in a single zip file)	csv.gz	317
ManualIdentification	Sound event identification made by contributors on a subsample of the original 1-min recordings	csv	1
AverageCompleteTable	For each unique site at a unique date and a unique hour, averaged values of acoustic indices and automated event recognition categories. This table also includes the corresponding Site, SunMoon, and ConfinementLevels information. Finally, given the original recording date and time in UTC+0 and knowing the associated timezone, a local date and time information was calculated	csv	1
AverageCompleteTable_nospeech	Same as AverageCompleteTable but the averaged values are only calculated on speech-filtered subsample of the acoustic collection	csv	1

Table 1. Silent Cities dataset description.

Response variable	Explanatory variable	Estimate	SE	Z value	*P* value
NDSI	Intercept	0.121	0.243	0.497	0.619
	Confinement level 1 *vs* no measures	0.035	0.012	2.832	0.005**
	Confinement level 2 and 3 *vs* no measures	0.051	0.014	3.535	<0.001***
	PCA axis: degree of anthropization	−0.190	0.052	−3.645	<0.001***
	Julian day: season	−0.083	0.005	−17.930	<0.001***
	Climate: dry *vs* tropical	0.498	0.366	1.358	0.174
	Climate: temperate *vs* tropical	0.018	0.230	0.077	0.938
	Climate: continental *vs* tropical	0.023	0.276	0.082	0.934
Birds	Intercept	−2.408	0.264	−9.137	<0.001***
	Confinement level 1 *vs* no measures	0.083	0.013	6.191	<0.001***
	Confinement level 2 and 3 *vs* no measures	0.207	0.015	14.074	<0.001***
	PCA axis: degree of anthropization	−0.115	0.044	−2.595	0.009**
	Julian day: season	−0.131	0.005	−28.449	<0.001***
	Climate: dry *vs* tropical	0.381	0.353	1.079	0.281
	Climate: temperate *vs* tropical	−0.153	0.238	−0.642	0.521
	Climate: continental *vs* tropical	−0.136	0.287	−0.476	0.634
Engine noise	Intercept	−4.844	0.207	−23.445	<0.001***
	Confinement level 1 *vs* no measures	−0.033	0.011	−2.887	0.004**
	Confinement level 2 and 3 *vs* no measures	−0.216	0.014	−15.130	<0.001***
	PCA axis: degree of anthropization	0.091	0.049	1.845	0.065
	Julian day: season	0.054	0.005	10.839	<0.001***
	Climate: dry *vs* tropical	−0.220	0.351	−0.626	0.531
	Climate: temperate *vs* tropical	0.022	0.220	0.100	0.920
	Climate: continental *vs* tropical	−0.152	0.265	−0.573	0.566

Table 2. Outputs of the full GLMMs relating the effects of COVID-19 confinement measures (alongside covariates) on NDSI, biophony (here, probability of bird calls) and anthropophony (here, probability of engine noise) levels at 08:00 am. Δ AIC values between the full and the null models are, from top to bottom, 593, 2056 and 1023, thus indicating that the full models were more informative than the null ones. SE: standard error of the estimate. $^{***}P < 0.001$, $^{**}P < 0.010$, $^{*}P < 0.050$. Confinement level 1 calls for "recommended not to leave home" and Confinement level 2 and 3 calls for "not allowed to leave home".

Data Records

The dataset[45] comprises the entire collection of acoustic recordings in Free Lossless Audio Codec (FLAC) format and associated metadata spread across several Comma Separated Value (CSV) tables (see Table 1). In order to

Variable	Definition	Possible value and range
Geophony_TempLevel	range of occupancy	0%/1-25%/25-50%/50-75%/75-100%
Wind	strength	0/1/2/3
Rain	strength	0/1/2
Wave	strength	0/1/2
Thunder	strength	0/1
Biophony_TempLevel	range of occupancy	0%/1-25%/25-50%/50-75%/75-100%
Bird	range of song types number	0/1-3/4-6/7-8/9-11/>11
Amphibian	range of song types number	0/1-3/4-6/7-8/9-11/>11
Insect	range of song types number	0/1-3/4-6/7-8/9-11/>11
Mammal	range of song types number	0/1-3/4-6/7-8/9-11/>11
Reptile	range of song types number	0/1-3/4-6/7-8/9-11/>11
Antropophony_TempLevel	range of occupancy	0%/1-25%/25-50%/50-75%/75-100%
Walking	presence/absence	0/1
Cycling	presence/absence	0/1
Beep	presence/absence	0/1
Car	sound intensity	0/1/2
Car honk	presence/absence	0/1
Motorbike	sound intensity	0/1/2
Plane	presence/absence	0/1
Helicopter	presence/absence	0/1
Boat	presence/absence	0/1
Other_motors	sound intensity	0/1/2
Shoot	presence/absence	0/1
Bell	presence/absence	0/1
Talking	presence/absence	0/1
Music	presence/absence	0/1
Dog bark	presence/absence	0/1
Kitchen sounds	presence/absence	0/1
Rolling shutter	presence/absence	0/1
Confidence level	low (0) to high confidence (5)	0/1/2/3/4/5

Table 3. Summary table of the typology used to manually describe the recordings.

protect privacy, only the preprocessed 10-second audio files with no speech identified are in direct open access on the OSF website (https://doi.org/10.17605/OSF.IO/H285U).

Technical Validation

To validate the Silent Cities dataset[45], we verified the veracity of the metadata reported by the contributors and consolidated the acoustic recordings collections by checking for device malfunctions. We also verified whether the automated acoustic measurements conducted on the recordings were coherent with aural human observations. Finally, proof of validity of the dataset to reflect urban soundscape changes due to stay-at-home requirements is presented. The three steps of this technical validation are detailed below.

First, we verified the quality of the data by manually verifying that the recordings were correctly attributed to their dedicated site with the help of the contributors. We also ran a manual cleaning of information given by the contributors to remove any personal information, such as address or GPS coordinates, and to correct spelling mistakes to ensure interoperability between tables. In addition, we verified the conformity of the protocol by automatically extracting information from the recording collection (*i.e.* frequency range, schedule of recordings) and reported observed modification of the protocol. We also automatically and manually verified the proper calculation of acoustic measurements and identified 10,724 files for which the calculation failed, probably due to file-related issues; these files were excluded from the dataset without affecting an entire site (*i.e.* no sites were excluded because of this issue). Finally, we checked for recorder device malfunction by making sure of a temporal variation of the dB value for each recorder, only one site was identified with a flat dB response, leading to its exclusion from the dataset.

Second, we confirmed that the automated soundscape measurements informed and aligned with real soundscape events. More specifically, we investigated whether the acoustic indices and audio tagging categories were representative of geophonic, biophonic and anthropophonic events detected manually by the contributors. To do

Final tag name	Corresponding labels in AudioSet Ontology	Category
Wind	Wind	Geophony
Rain	Rain	
River	Stream/Waterfall	
Wave	Ocean	
Thunder	Thunderstorm	
Bird	Bird vocalization, bird call, bird song/Pigeon, dove/Crow/Owl/Gull, seagull	Biophony
Amphibian	Frog	
Insect	Insect	
Mammal	Rodents, rats, mice/Canidae, dogs, wolves	
Reptile	Snake	
Walking	Run/Walk, footsteps	Anthropophony
Cycling	Bicycle/Bicycle bell	
Beep	Reversing beeps	
Car	Car passing by/Tire squeal	
Car honk	Vehicle horn, car horn, honking	
Motorbike	Motorcycle	
Plane	Aircraft engine/Fixed-wing aircraft, airplane	
Helicopter	Helicopter	
Boat	Motorboat, speedboat/Ship/Sailboat, sailing ship	
Other motors	Traffic noise, roadway noise	
Shoot	Gunshot, gunfire	
Bell	Chime/Jingle bell/Cowbell/Church bell/Change ringing (campanology)	
Talking	Speech/Hubbub, speech noise, speech babble/	
Music	Music	
Dog bark	Dog	
Rolling shutter	Power windows, electric windows	
Kitchen sounds	Door/Cupboard open or close/Drawer open or close/Dishes, pots, and pans/ Cutlery, silverware/Chopping (food)/Sink (filling or washing)/Water tap, faucet/Kettle whistle/ Microwave oven/Blender	

Table 4. Mapping between the Silent Cities tags and the labels from the AudioSet ontology. Each tag is computed using the maximum probability output from the pretrained network among the corresponding Audioset labels. Finally, the three tags Antropophony, Geophony and Biophony are computed using the maximum tag probability in the category.

so, we conducted a series of univariate generalized linear mixed-effect models (GLMMs; 'glmmTMB' package[68],) in R v4.2.1. We tested independently the presence/absence of geophonic, biophonic and anthropophonic events within the 1351 1-min recordings (*i.e.* response variables) in relation to acoustic indices and tagging types (*i.e.* explanatory variables). Models were fitted with a binomial error distribution and a logit link function. We considered the identity of contributors as a random effect to avoid pseudoreplication. We also implemented a first-order autoregressive function to account for serial autocorrelation in residuals. Statistical assumptions were visually assessed using model diagnostics (i.e. Quantile-Quantile plot, residuals vs fitted plot) with the DHARMa package[69]. The acoustic indices were linked to geophonic, biophonic, or anthropophonic events, albeit to varying degrees (Fig. 2b). For instance, the presence of biophonic events was associated with greater values of EAS and ECV and lower values of dB. Audio tagging categories effectively captured the intended soundscapes they aimed to portray (Fig. 2b).

Third, we assessed the validity of the dataset in evaluating the impact of stay-at-home requirements on soundscapes. In a first step, we plotted the mean values of biophony and anthropophony levels (here defined as the maximum probability of having a biophonic and anthropophonic event in the 1-min recording, respectively) per site recorded at each hour (all protocols combined). As expected, we observed temporal patterns in biophony and anthropophony levels throughout the day (Fig. 2c). Regardless of the time of day, biophony levels were greater during the period when leaving home was not permitted (*i.e.* confinement level 2 or 3) compared to the other periods, while the opposite pattern was true for anthropophony. In a second step, we modeled changes in the values of acoustic indices as well as biophony and anthropophony levels (*i.e.* response variables) in relation to the containment measures (*i.e.* explanatory variables) using GLMMs with a beta distribution and a log link function. We aimed to provide a proof of validity and therefore limited the analysis to the expert protocol and all recordings collected at 8:00 am (*i.e.* peak of biophonic and anthropophonic events; Fig. 2d). We focused on NDSI for the acoustic index and the probability of bird calls and engine noise indicated by the automatic sound event recognition in the recordings as proxies of biophony and anthropophony levels, respectively. We added as covariates in the models: (i) Julian day to consider seasonal changes in biological and anthropogenical sounds, (ii) the first Principal Component Analysis axis depicting the level of anthropization in the landscape

Response variable	Explanatory variable	Estimate	SE	*t* ratio	*P* value
NDSI	Confinement level 1 *vs* no measures	0.035	0.012	2.832	0.013*
	Confinement level 2 and 3 *vs* no measures	0.051	0.014	3.535	0.001**
	Confinement level 2 and 3 *vs* Confinement level 1	0.016	0.011	1.464	0.309
Birds	Confinement level 1 *vs* no measures	0.083	0.013	6.191	<0.001***
	Confinement level 2 and 3 *vs* no measures	0.207	0.015	14.074	<0.001***
	Confinement level 2 and 3 *vs* Confinement level 1	0.124	0.011	11.272	<0.001***
Engine noise	Confinement level 1 *vs* no measures	−0.327	0.011	−2.887	0.011*
	Confinement level 2 and 3 *vs* no measures	−0.216	0.014	−15.130	<0.001***
	Confinement level 2 and 3 *vs* Confinement level 1	−0.183	0.01	−16.999	<0.001***

Table 5. Results of the post hoc pairwise comparisons applied to the GLMMs relating the effects of COVID-19 confinement measures (alongside covariates) on NDSI, biophony (here, probability of bird calls) and anthropophony (here, probability of engine noise) levels at 08:00 am. SE: standard error of the estimate. $^{***}P < 0.001$, $^{**}P < 0.010$, $^{*}P < 0.050$. Confinement level 1 calls for "recommended not to leave home" and Confinement level 2 and 3 calls for "not allowed to leave home".

surrounding the recordings, and (iii) the climate type. Continuous covariates were scaled (mean = 0; SD = 1) to avoid convergence issues. We considered as random effects site identity nested within country to account for hierarchical clustering within data and recorder type, due to potential sensitivity differences between devices. Due to the limited data collected during the strictest containment period, we combined data from the two periods when leaving home was not permitted. The same approach as outlined previously was employed for model validation (note that the validity of the statistical assumptions, assessed using Quantile-Quantile and residuals vs fitted plots, was only partially met for the engine noise model). Full models were more informative than the null ones with differences in Akaike Information Criterion scores > 500. Finally, we conducted Tukey's post hoc multiple comparison test to investigate pairwise differences in NDSI values and biophony and anthropophony levels between the three COVID-19 containment measures investigated. Overall, we found that COVID-19 lockdown had positive effects on NDSI values and biophony levels and negative effects on anthropophony levels. After accounting for seasonal and landscape effects, our models suggest that NDSI values and biophony levels were significantly greater during the periods when leaving home was not recommended or permitted, compared to the period with no measures (Fig. 2d; Table 2). There were also higher biophony levels during the period when leaving home was not permitted than during the period with when leaving home was not recommended. The opposite patterns were found for the anthropophony levels, with significantly lower values measured during the periods when leaving home was not permitted compared to the other periods, albeit the differences were of smaller magnitude (Fig. 2d; Table 5). Altogether, our preliminary analysis revealed potential changes in soundscape patterns that can be attributed to containment policies, these changes being above expected differences due to climate.

Usage Notes

The Silent Cities dataset could be considered for multiple applications. In the specific fields of bio/ecoacoustics, it could be used to study the effect of containment measures on urban soundscapes[29], to improve the performance of acoustic indices in urban environments[70] and to gain a deeper understanding of the interplay between biophony and urban environment characteristics[71]. In the field of machine learning (machine listening, deep learning), it will allow the testing of difficult cases of generalization in sound event recognition from one site to another, due to the variety of sampled sites[72]. In the interdisciplinary field of territorial sciences (e.g. economic geography, territorial economics, spatial planning, urban engineering sciences), it will make it possible to analyze the links between the levels of economic activity of a city and the levels of noise pollution. Finally, for environmental sciences interested in well-being and relationships between humans and non-humans within urban socio-ecosystems (e.g. environmental and health psychology, landscape design, environmental geography, etc.), this dataset opens up opportunities for the qualitative study of individual and subjective perceptions of the different soundscape configurations collected. More broadly, we aim for this international and collaborative dataset to be usefully mobilized in any research working to make better coexistence between humans and non-humans possible, and thus working to maintain the Earth's habitability conditions for all of them.

The Silent Cities dataset[45] is available under the terms of a Creative Commons Attribution 4.0 International waiver (CC-BY 4.0, https://creativecommons.org/licenses/by/4.0/). The CC-BY-4.0 waiver facilitates the discovery, re-use, and citation of the dataset. When using all or part of the dataset, we require anyone to cite both the dataset[45] and this publication.

Code availability

The recording manipulation and acoustic measurements were run using Python, https://github.com/brain-bzh/SilentCities and the analyses were run on R https://github.com/agasc/SilentCities-R.

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Author contributions

S.C. introduced the concept; S.C., A.G., J.S.P.F. and N.F. designed the protocol; S.C., A.G., J.S.P.F., N.P., N.F. and the Silent Cities Consortium collected the soundscape recordings; A.G., N.P. managed the data; A.G., J.S.P.F., N.P. and N.F. conducted the data analysis; A.G. and J.S.P.F. conducted the technical validation. N.F. was in charge of high performance computing; S.C., A.G., J.S.P.F., N.P. and N.F. wrote the initial draft; all authors including the Silent Cities Consortium reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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