Dramatic Lockdown Fossil Fuel CO2 Decrease Detected by Citizen Science-Supported Atmospheric Radiocarbon Observations

Jocelyn C. Turnbull,* Lucas Gatti Domingues, and Nikita Turton

ABSTRACT: COVID-19 lockdowns resulted in dramatic changes to fossil fuel CO2 emissions around the world, most prominently in the transportation sector. Yet travel restrictions also hampered observational data collection, making it difficult to evaluate emission changes as they occurred. To overcome this, we used a novel citizen science campaign to detect emission changes during lockdown and engage youth in climate science. Citizen scientists collected grass samples from their garden or local park, from which we analyzed the radiocarbon content to infer the recently added atmospheric fossil fuel CO2 mole fraction at each sampling location. The local fossil fuel CO2 mole fractions during lockdown were compared with a “normal” nonlockdown period. Our results from 17 sites in five cities around New Zealand demonstrate dramatic reductions in traffic emissions of 75 ± 3% during the most severe lockdown restriction period. This is consistent with sparse local traffic count information and a much larger decrease in traffic emissions than reported in global aggregate estimates of emission changes. Our results demonstrate that despite nationally consistent rules on travel during lockdown, emission changes varied by location, with inner-city sites typically dominated by bus traffic showing smaller decreases in emissions than elsewhere.

KEYWORDS: fossil fuel CO2, radiocarbon, lockdown, emissions, citizen science

1. INTRODUCTION

The impossibility of accessing sites and collecting samples during COVID-19 lockdown led us to use a novel citizen science campaign to reconstruct fossil fuel CO2 (CO2ff) emissions from grass samples collected from five cities around New Zealand. While CO2 emissions have gradually increased over the last decades to about 10 gigatonnes of carbon per year in 2019,1 the 2020 COVID-19 lockdowns resulted in dramatic, but often short-lived, widespread CO2ff emission decreases.2,3 Changes in air quality metrics have been evaluated through atmospheric and remote sensing observations at many locations around the world,4–8 but greenhouse gas changes due to COVID-19 have been challenging to evaluate from atmospheric observations largely because changes in the CO2ff atmospheric enhancement are expected to be modest relative to the large and variable CO2 background. Thus, the first estimates of CO2ff emission changes were based on the extrapolation of inventories using proxy data.2,7 Atmospheric observations of CO2ff during COVID-19 lockdowns have not yet been reported, and only a small number of studies have detected changes from atmospheric observations of total CO2.9–12

14C is well recognized as an ideal tracer for CO2ff since fossil fuels have been out of contact with the atmosphere for millions of years, and all 14C initially present has long since decayed radioactively. In contrast, other CO2 sources contain 14C in roughly the same proportion as the current atmosphere. Therefore, the 14C content of atmospheric CO2 can be used to determine the CO2ff content.13–15

Plant material provides a natural sampling method to determine the radiocarbon (14C) content of atmospheric CO2. When plants photosynthesize, they use the carbon from CO2 to grow, and faithfully record the 14C content of the CO2 assimilated from the atmosphere. Tree rings, leaves, and other plant material are thus widely used to reconstruct past atmospheric 14C content.16 Moreover, the first direct evidence that fossil fuel CO2 emissions were driving changes in atmospheric CO2 came from 14C measurements in tree rings.13 While tree rings record the 14C content of the atmosphere for each year of growth,13 leaves can be used to sample the atmosphere over the shorter period of their growth.17,18 Grass is particularly useful for short-term sampling because of the rapid growth of the grass blades that can represent just a few days or weeks of growth.18 Short-lived plant material has thus been widely used to determine atmospheric 14C content.
and derive local patterns of CO$_{2ff}$ mole fraction in contemporary samples.$^{17-20}$

During New Zealand’s most severe lockdown from 26 March to 27 April 2020, termed “Level 4”, most people were confined to their family bubble and no travel more than 5 km from home was allowed. Almost all businesses and industries were closed, with only pharmacies, medical services, supermarkets, and petrol stations remaining open. It was not possible to obtain travel exemptions for scientific research. Instead, we initiated a citizen science campaign to allow monitoring of CO$_{2ff}$ emission changes during this unique severely restricted travel period. We recruited citizen scientists from around New Zealand to collect short-lived grass samples from their own lawn, a local park, or a nearby roadside. The weekly samples were collected during lockdown and through until return to near-normal conditions. Each sample was analyzed for $^{14}$C content, from which local fossil fuel CO$_2$ mole fraction was determined, and emission changes inferred.

2. METHODS

2.1. Sample Collection. More than 400 people from around New Zealand signed up to the Great Greenhouse Gas Grass Off initiative, and in many cases, children were the main sample collectors under the guidance of their parents or caregivers. Citizens were asked to choose a local grass patch, ensuring that they did not violate the lockdown travel and social distancing requirements. They were asked to take an initial sample, cutting the grass down to the white roots, and store the dated and labeled sample in a freezer. Each week, they were reminded to collect a new regrowth sample from the same grass, continuing through Level 4 (March 26 to April 27, 2020) to the less restrictive Level 3 (April 28 to May 13, 2020), Level 2 (May 14 to June 8, 2020) and the removal of in-country travel and work restrictions in Level 1 (from June 9, 2020). Participants were encouraged to engage in the science, with regular social media updates explaining the methods and reporting results as samples were measured.

Ultimately, 110 sample sets were submitted to our laboratory, along with many detailed handwritten letters, maps, and photographs. From these, we selected 26 sample sets that contained sufficient samples to track emissions during the full lockdown period and return to normal conditions; were of sufficient quality for $^{14}$C analysis; and from locations where substantial local CO$_{2ff}$ emissions might be anticipated.

Seventeen of these sites from five cities around New Zealand (Figure 1) proved to have robust, interpretable CO$_{2ff}$ signals and are presented here. The remaining sampled nine sites are excluded because they either had small to negligible CO$_{2ff}$ signals and therefore emission changes could not be determined with statistical significance or showed large variability in CO$_{2ff}$ during the Level 1 “normal” conditions (Section 2.4). Of the 17 selected sites, four are in New Zealand’s largest city (population 1.5 million), seven are in the Wellington region (population 400,000), three in Christchurch (population 400,000), two in Hamilton (population 200,000), and one is in the medium-sized town of Gisborne (population 40,000). All of New Zealand’s towns and cities have modest population density, ranging from about 2400 people/km$^2$ in Auckland to 1000 people/km$^2$ in Gisborne.

All of these sites are within 20 m of a road; maps of each site are given in Figures S2–S4. The Auckland sites are near urban (AKL_ANZACAve, AKL_BallantynesSq) and suburban roads (AKL_Grafton, AKL_GreyLynn). In Wellington, three sites are...
adjacent to motorways or major arterial routes with normally heavy traffic (WLG_SH1Paekakariki, WLG_SH2Riverstone, WLG_AoteaLagoon), and one is at a traffic light intersection at the terminus of a major motorway (WLG_SH1WillisSt). Two Wellington sites are located on the grassed median on an inner-city street, one adjacent to a traffic light intersection (WLG_CambridgeTce1) and the second site about 100 m south (WLG_CambridgeTce2). The seventh Wellington site is on a suburban street (WLG_WaioneSt). Two Christchurch sites are on urban streets (CHC_BarbadoesSt, CHC_BroughamSt), and the third (CAN_Lincoln) is a major arterial route through farmland just outside the city proper. The Hamilton and Gisborne sites are all suburban streets (HML_MasseySt, HML_PeachgroveRd, GIS_OrmondRd).

Citizen scientists were asked to collect samples by harvesting the green grass leaves down to the white roots. The following sample then represents growth during the period since the last sample was collected, typically one week. The growth period of the first sample of each series is not well known but estimated to be the two weeks preceding the sample collection. Harvested grass length varied between 1 and 5 cm. Samples from an individual site were always the same species (having been harvested from regrowth of the same plant), but grass type may differ across different sites. Grass assimilates carbon only during daylight hours when sunlight enables photosynthesis, so each grass sample represents daylight hours for the days since the last sample was harvested. Since we measure the 14C content of assimilated CO2, varying growth rates at different sites and times do not impact the 14C content and derived CO2 mole fractions.

The growth period must always be an approximation, as plant growth and CO2 assimilation vary depending on daylight hours, irradiance, meteorology, and plant growth cycles. For our sampling period, daylight hours gradually decreased each week so that samples collected during Level 1 are biased to a shorter part of the day than those during Level 4. The samples are also biased toward sunny periods. Although we asked citizen scientists to collect the full regrowth each week, it is possible, or even likely, that some samples might include growth from the previous week(s). It is also possible that some fraction of the new growth is derived from carbon assimilated over previous weeks and remobilized into the newly grown grass leaves. Nonetheless, each sample approximates the 14C content of atmospheric CO2 at that location during daylight hours over the period of sample growth.

2.2. Radiocarbon Analysis. For each sample, the full length of a grass blade (or blades) was selected. Length varied by sampling site and date, ranging from 1 cm to 5 cm in length. If insufficient weight was obtained from a single blade of grass, multiple blades were combined. Since grass blades grow from the base, by selecting the full length of a blade, each blade should represent the full time period since the last sample was collected, noting the sampling biases due to when carbon is assimilated as discussed in Section 2.1.

Selected samples were prepared and measured by standard 14C techniques, which included an acid wash to remove surface material, combustion to CO2 gas by elemental analyzer, and reduction to graphite over iron catalyst. 14C measurement was by accelerator mass spectrometry. Reported uncertainties were assessed by the variability of replicate samples prepared from separate grass blades collected at the same site and date. We found an overall repeatability of 2.1% from six replicate samples encompassing both clean air and polluted sites (Figure S1). This is somewhat higher than the assessed 14C measurement uncertainty of 1.7% and indicates that there is a modest amount of additional uncertainty introduced by CO2 assimilation or grass collection. We increased the assigned uncertainties by 1.2% (added in quadrature) to include this additional source of variability, resulting in final 14C uncertainties of 2.0–2.2% (Supporting Dataset).

2.3. Determination of CO2ff. CO2ff was determined from measured Δ14C, such that

\[ \text{CO}_{2\text{ff}} = \frac{\text{CO}_{2\text{bg}}(\Delta_{\text{obs}} - \Delta_{\text{bg}})}{\Delta_{\text{ff}} - \Delta_{\text{bg}}} - \beta \]  

where \( \text{CO}_{2\text{bg}} \) is the background CO2 mole fraction, in this case determined from the mean CO2 value at Baring Head, near Wellington (Figure 1) over the full sampling period. \( \Delta_{\text{obs}} \) is the observed 14C in the grass sample. \( \Delta_{\text{ff}} \) is the 14C of fossil fuel CO2 (~100‰ by definition for 14C-free material. \( \Delta_{\text{bg}} \) is the 14C of background air for the same time period, for which we also used the mean measured 14C of 7.1 ± 0.5‰ at Baring Head for March–July 2020 (extended dataset available at https://gaw.kishou.go.jp/). There is a slight, but not significant, downward trend in the Baring Head 14C values (Figure 2). We tested the impact of varying the background to account for this trend, but this did not significantly alter the calculated CO2ff values.

![Figure 2](https://example.com/fig2.jpg)

Figure 2. Δ14C measured at five sites with little local fossil fuel CO2 influence. Green lines indicate lockdown levels Changes in lockdown level from highest (L4) to lowest (L1) are indicated by the green vertical lines. The blue line indicates the assigned background Δ14C value derived from Baring Head Δ14C during measurements. Error bars are the assigned one-sigma uncertainty as described in the text.

\( \beta \) is a correction for the slightly elevated Δ14C in heterotrophic respiration, and we use a value of ~0.5 ± 0.25 ppm in CO2ff. To test this correction, we used grass samples collected for this study from a rural site near Whangarei (Figure 2) and Level 4 and Level 3 at four windy suburban sites in Wellington (WLG_WyndrumAve, WLG_TamaSt, WLG_MitchellSt and WLG_NorthlandPark, Figure 2) which together had mean Δ14C of 8.0 ± 0.3‰. Assuming no CO2ff influence in these samples, the slight elevation in Δ14C with respect to Baring Head was used to diagnose the heterotrophic respiration bias term as ~0.4 ± 0.2 ppm, comparable to the canonical value of ~0.5 ± 0.25 ppm. We note that WLG_MitchellSt and WLG_NorthlandPark do appear to have a modest CO2ff signal during Level 2 and Level 1, and these data are not used in the background analysis.

2.4. Estimation of CO2ff Emission Rate Changes from CO2ff Mole Fraction Observation. Ultimately, we are...
Figure 3. continued
interested in the CO$_{2ff}$ emission rate, whereas our observed CO$_{2ff}$ from the grass samples is a function of both the local CO$_{2ff}$ emission rate and the meteorological conditions transporting emitted CO$_{2ff}$ to the grass location.

First, we estimate the area of influence for each grass sample. Grass necessarily grows within a few centimeters of the Earth’s surface. The atmospheric flow this close to the ground, particularly among rapidly growing grass, is difficult to assess and made even more complex at urban sites with nearby buildings, trees, and other topographic features.

Still, we used the WindTRAX Lagrangian stochastic model to estimate the relative influence of nearby sources. Local wind data was available at only one of our sites, which was directly adjacent (within 5 m) to an air quality monitoring station (WLG_SH1WillisSt). We choose three representative weeks of wind data and ran the WindTRAX model for a receptor 50 cm above the surface. The model estimates that emissions within 20 m of the grass will have a 10-fold larger influence than those 50 m away, indicating that the closest sources will strongly dominate the observed CO$_{2ff}$ mole fraction. All 17 selected sites were

Figure 3. Observed CO$_{2ff}$ mole fractions determined from $^{14}$C measurements in grass for 17 sites in five cities around New Zealand: Auckland (AKL), Wellington (WLG), Christchurch (CHC/CAN), Hamilton (HML), and Gisborne (GIS). Changes in lockdown level from highest (L4) to lowest (L1) are indicated by the green vertical lines. Error bars are the assigned one-sigma uncertainty as described in the text.
within 20 m of busy roads, so the observed CO$_{2\text{ff}}$ signals are expected to be dominated by traffic emissions (Figures S2 and S3). CO$_{2\text{ff}}$ sources such as residential and commercial heating could also impact emissions at these sites, particularly since the lockdown required the vast majority of people to stay home during Level 4. Residential CO$_{2\text{ff}}$ emissions are modest in New Zealand, representing 5% of urban CO$_{2\text{ff}}$ emissions versus 40% from traffic under normal conditions and are predominantly in the mornings and evenings rather than daytime hours when the grass is assimilating carbon. Wood burning is a relatively common residential heating source in New Zealand but does not contribute to CO$_{2\text{ff}}$.

One site located more than 100 m from the nearest road (WLG-GurneyRd, Figures 4 and S4) showed a trend broadly consistent with the patterns seen at other sites, but the CO$_{2\text{ff}}$ mole fractions even during Level 1 were too small to diagnose changes through time and thus excluded from the dataset.

Figure 4. Observed CO$_{2\text{ff}}$ mole fractions for four sites that were rejected from analysis due to either: variable CO$_{2\text{ff}}$ during Level 1, or signals that are too small to interpret.

Figure 5. CO$_{2\text{ff}}$ change in Level 4 lockdown relative to Level 1 at 17 sites around New Zealand, expressed as the reduction in CO$_{2\text{ff}}$ mole fraction in Level 4 vs level 1. Error bars represent the calculated uncertainty in the emission reduction for each site.
Second, day-to-day and synoptic scale meteorological variability such as changing wind direction and speed can result in large differences in CO\textsubscript{2ff} mole fraction at the same location, even if the emission rate is constant. Yet for this study utilizing citizen science, we were unable to collect local meteorological information at each site. First, we considered whether seasonal changes in boundary layer height could bias our results, but only modest changes in daytime boundary layer height are observed in New Zealand cities during our sampling period from autumn (March–April–May) to winter (June–July–August).\textsuperscript{27} Second, we evaluated the impact of meteorological variability at each site from the week-to-week variability in observed CO\textsubscript{2ff} during the last few weeks of samples collected under Level 1 normal conditions. At most sites, the week-to-week variability in CO\textsubscript{2ff} across all samples collected in Level 1 is no larger than the measurement uncertainty bounds (Figure 3 and Supporting Dataset). This indicates that week-to-week variability in meteorology did not significantly influence the observed CO\textsubscript{2ff} mole fractions. Week-to-week changes in CO\textsubscript{2ff} emission rate will therefore be proportional to week-to-week changes in CO\textsubscript{2ff} mole fraction. Three sites did show substantial week-to-week differences in CO\textsubscript{2ff} mole fraction during Level 1 and at other levels (AKL_FerndaleRd, WLG_SH2RiverRd, Figure 4). We hypothesize that at these two sites, specific local sources combined with week-to-week changes in wind patterns could drive the variability and these sites are excluded from further analysis. A third site, WLG_HuttRiverTaita, showed a pattern broadly consistent with traffic emissions, but a single observation during Level 1 showed a large discrepancy (Figure 4), which is most likely associated with a labeling error. Nonetheless, we excluded this site from further analysis.

Without explicit, detailed atmospheric transport information for each site, we still cannot infer absolute CO\textsubscript{2ff} emission rates from the observed CO\textsubscript{2ff} mole fractions, yet changes in the CO\textsubscript{2ff} emission rate can be evaluated from the week-to-week change in observed CO\textsubscript{2ff} mole fraction. This is simply done by determining the ratio of CO\textsubscript{2ff}(Level 4) to CO\textsubscript{2ff}(Level 1).

3. RESULTS

All sites show the lowest CO\textsubscript{2ff} mole fractions during Level 4 (strictest lockdown restrictions), gradually increasing through Level 3, Level 2, and then staying consistent at higher values during Level 1 (normal) (Figure 3). A few outlier samples suggest unusual emissions during particular weeks or could also reflect sampling or labeling errors that are difficult to control for in a citizen science initiative.

The range of observed CO\textsubscript{2ff} values varies by site, depending on proximity to and strength of local emission sources, with sites closest to busy roads showing higher CO\textsubscript{2ff} mole fractions than sites further from emission sources. The drop in emissions during Level 4 compared to Level 1 varies by site from −36 to −99%, with a mean of −75 ± 3% across all 17 sites in five New Zealand regions (Figure 5). Our 17 sites encompass motorways, arterial routes, and urban and suburban streets from five different cities. This breadth of sites means that this small number of sites reasonably, but imperfectly, represent traffic emission changes across New Zealand.

Most sites are within 20 m of roads (Figures S2–S4), and therefore traffic emissions are the dominant emission source for these locations. In our observations, two sites in Auckland (AKL_ANZACAve and AKL_BallantynesSq) show smaller emission decreases during Level 4 than the other sites (−36 ± 19 and −50 ± 17%, Figures 3 and 5). AKL_ANZACAve is in a small park adjacent to a normally busy city street on a hill slope, surrounded by apartment buildings (Figure S1). This street is heavily trafficked by buses which continued to operate during Level 4 lockdown and is likely the reason for the smaller emission change. The site may also be influenced by nearby residential CO\textsubscript{2ff} emissions, which are not expected to have dropped substantially during Level 4 lockdown. This result is consistent with a study of pollutants in central Auckland, suggesting that lockdown decreases in traffic-associated pollutants may have been more modest in the central business district than elsewhere, likely due to ongoing bus traffic in this area.\textsuperscript{1,28}

Samples were also collected from two sites 100 m apart on Cambridge Terrace in the Wellington central business district, both on the median of the same divided city street (WLG_CambridgeTce1, WLG_CambridgeTce2, Figure 3). The first site is within 10 m of an intersection and shows a step change in CO\textsubscript{2ff} mole fraction in Level 2, whereas the second site midway between intersections shows a more gradual increase in emissions through Level 2, as do all other sites in Wellington and around New Zealand (Figure 3). We hypothesize that in Level 2, the intersection became busy enough that traffic routinely backed up, resulting in a jump in emissions at this location. At the second site, traffic continued to flow, and vehicles did not idle close to the sampling site as often, resulting in a slower increase in emissions as people gradually resumed their normal travel (Figure 3).

4. DISCUSSION: COMPARISON WITH OTHER METRICS FOR EMISSION CHANGES

A global study of COVID-19-related CO\textsubscript{2ff} emission changes based on proxy data\textsuperscript{2} assigned surface transport emission reductions for Level 4 based on a combination of Apple Mobility data and TomTom urban congestion data. They determined a −47% change in traffic emissions for the "Oceania" region compromising New Zealand and Australia, substantially different than our observed decrease of −75 ± 3%. This is likely due to aggregating across two countries with different lockdown policies. The Apple mobility data for New Zealand alone (https://www.apple.com/covid19/mobility/) indicates a change in driving requests of −81% in Level 4 relative to the Level 1 recovery period. The slightly larger reduction in traffic implied by the Apple Mobility Data than in our CO\textsubscript{2ff} observations could be because changes in driving requests are not an exact proxy for emission changes.\textsuperscript{29}

Waka Kotahi New Zealand Transport Agency traffic count data shows a decrease in traffic counts during Level 4 relative to Level 1 of −75% in Auckland (two locations), −79% in Wellington, −74% in Christchurch, and −71% in Hamilton (https://opendata-nzta.opendata.arcgis.com/search?q=traffic). No traffic count data was available for Gisborne. In no case is the traffic count data co-located with our CO\textsubscript{2ff} observations. On average, these traffic count data indicate a change in traffic of −75% during Level 4, consistent with our observed changes in CO\textsubscript{2ff} emissions. However, our results demonstrate spatial variability in emission changes that is not captured by the traffic count data collected from fewer sites. Further, while traffic counts and traffic CO\textsubscript{2ff} emissions are very strongly correlated during the 2020 COVID-19 lockdowns, it might be expected that as fuel efficiency improves and electric vehicles are more widespread in the near future, traffic counts and traffic CO\textsubscript{2ff} emissions will decouple. This study demonstrates that roadside...
14C sampling, either in grass or direct from atmospheric samples, could allow tracking of such changes.

5. CONCLUSIONS

Atmospheric observations of CO2eff derived from 14C content of grass samples demonstrated a −75 ± 3% change in traffic emissions in New Zealand during the highest level of COVID-19 lockdown. This result is broadly consistent with changes in traffic counts, but the larger number of sampling sites reveals local differences in emission reductions. Our results demonstrate that while broad regional estimates are likely sufficient for inferring global emission changes, local studies such as ours are needed to elucidate the detail of local emission changes at a level relevant to policymakers. Our results show a strong relationship between changes in CO2eff emissions and in traffic counts, and suggest that future decoupling of these two metrics, as fuel efficiency and electrification increase, could be observed through 14C sampling in grass or direct atmospheric measurements.

Our inability to access the field combined with the population being kept at home created the perfect opportunity to engage citizens in science. Their contribution was an essential part of this project, proving to be an effective method to gather valuable high-quality scientific information. The simplicity of the sample collection method, and participation of the public, proved to be an excellent route to public engagement in climate change and emissions mitigation.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c07994.

Measurement precision and maps of each individual measurement site (PDF)
Radiocarbon measurements and calculated CO2eff for every measured sample (XLSX)

AUTHOR INFORMATION

Corresponding Author
Jocelyn C. Turnbull – Rafter Radiocarbon Laboratory, GNS Science, Lower Hutt 5010, New Zealand; CIERES, University of Colorado at Boulder, Boulder, Colorado 80309, United States; orcid.org/0000-0002-0306-9658; Phone: +64 4 570 4726; Email: j.turnbull@gns.cri.nz

Authors
Lucas Gatti Domingues – Rafter Radiocarbon Laboratory, GNS Science, Lower Hutt 5010, New Zealand
Nikita Turton – Rafter Radiocarbon Laboratory, GNS Science, Lower Hutt 5010, New Zealand

Complete contact information is available at: https://pubs.acs.org/doi/10.1021/acs.est.1c07994

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work would not have been possible without the support of the 110 families who collected and submitted grass samples from around New Zealand during lockdown. We particularly appreciate the efforts of the many children who became so actively involved. A special thanks to Ashleigh Prentice, a citizen scientist who volunteered to document more than 1000 grass samples as they arrived in our lab. The social media campaign that communicated our work would not have been possible without Janet Skilton, Benj Berryman, and Eleanor Deacon. As always, the Rafter Radiocarbon Lab staff (Margaret Norris, Albert Zondervan, Jenny Dahl, Cathy Ginnane, Julia Collins, Jeremy Parry-Thompson, and Taylor Ferrick) made a careful set of measurements. Thanks to Gordon Brailsford and Sara Mikaloff Fletcher (NIWA) for suggesting this project. This work was funded by the New Zealand Ministry for the Environment and the GNS Science Strategic Science Investment Fund.

REFERENCES

(1) Le Quéré, C.; Moriarty, R.; Andrew, R. M.; Peters, G. P.; Ciais, P.; Friedlingstein, P.; Jones, S. D.; Sitch, S.; Tans, P.; Arneth, A.; Boden, T. A.; Bopp, L.; Bozec, Y.; Canadell, J. G.; Chini, L. P.; Chevallier, F.; Cosca, C. E.; Harris, I.; Hoppema, M.; Houghton, R. A.; House, J. I.; Jain, A. K.; Johannessen, T.; Kato, E.; Keeling, R. F.; Kitidis, V.; Klein Goldewijk, K.; Koven, C.; Landa, C. S.; Landschützer, P.; Lenton, A.; Lima, I. D.; Marland, G.; Mathis, J. T.; Metzl, N.; Nojiri, Y.; Olsen, A.; Ono, T.; Peng, S.; Peters, W.; Pfeil, B.; Poulter, B.; Raupach, M. R.; Regnier, P.; Rödenbeck, C.; Saito, S.; Salesby, J. E.; Schuster, U.; Schwinger, J.; Séférian, R.; Ségschneider, J.; Steinhoff, T.; Stocker, B. D.; Sutton, A. J.; Takahashi, T.; Tilbrook, B.; van der Werf, G. R.; Ivyo, N.; Wang, Y. P.; Wanninkhof, R.; Wiltshire, A.; Zeng, N. Global carbon budget 2015. Earth Syst. Sci. Data 2016, 7, 47–85.
(2) Le Quéré, C.; Jackson, R. B.; Jones, M. W.; Smith, A. J. P.; Abernethy, S.; Andrew, R. M.; De-Gol, A. J.; Willis, D. R.; Shan, Y.; Canadell, J. G.; Friedlingstein, P.; Creutzig, F.; Peters, G. P. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Change 2020, 10, 647–653.
(3) Liu, Z.; Ciais, P.; Deng, Z.; Lei, R.; Davis, S. J.; Feng, S.; Zheng, B.; Cui, D.; Dou, X.; Zhu, B.; Guo, R.; Ke, P.; Sun, T.; Lu, C.; He, P.; Wang, Y.; Yue, X.; Wang, Y.; Lei, Y.; Zhou, H.; Cai, Z.; Wu, Y.; Guo, R.; Han, T.; Xue, J.; Boucher, O.; Boucher, E.; Chevallier, F.; Tanaka, K.; Wei, Y.; Zhong, H.; Kang, C.; Zhang, N.; Chen, B.; Xi, F.; Liu, M.; Breon, F. M.; Lu, Y.; Zhang, Q.; Guan, D.; Gong, P.; Kammen, D. M.; He, K.; Schellnhuber, H. J. Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. Nat. Commun. 2020, 11, No. 5172.
(4) Bray, C. D.; Nahas, A.; Battye, W. H.; Aneja, V. P. Impact of lockdown during the COVID-19 outbreak on multi-scale air quality. Atmos. Environ. 2021, 254, No. 118386.
(5) Talbot, N.; Takada, A.; Bingham, A. H.; Elder, D.; Lay Yee, S.; Golubiewski, N. E. An investigation of the impacts of a successful COVID-19 response and meteorology on air quality in New Zealand. Atmos. Environ. 2021, 254, No. 118322.
(6) Potts, D. A.; Marais, E. A.; Boesch, H.; Pope, R. J.; Lee, J.; Drysdale, W.; Chipperfield, M. P.; Kerridge, B.; Siddans, R.; Moore, D. P.; Remedios, J. Diagnosing air quality changes in the UK during the COVID-19 lockdown using TROPOMI and GEOS-Chem. Environ. Res. Lett. 2021, 16, No. 054031.
(7) Brandao, R.; Foroutan, H. Air Quality in Southeast Brazil during COVID-19 Lockdown: A Combined Satellite and Ground-Based Data Analysis. Atmosphere 2021, 12, No. 583.
(8) Grange, S. K.; Lee, J. D.; Drysdale, W. S.; Lewis, A. C.; Hugelin, C.; Emmenegger, L.; Carslaw, D. C. COVID-19 lockdowns highlight a risk of increasing ozone pollution in European urban areas. Atmos. Chem. Phys. 2021, 21, 4169–4185.
(9) Turner, A. J.; Kim, J.; Fitzmaurice, H.; Newman, C.; Worthington, K.; Chan, K.; Wooldridge, P. J.; Köhler, P.; Frankenberg, C.; Cohen, R. C. Observed impacts of COVID-19 on urban CO2 emissions. Geophys. Res. Lett. 2020, 47, No. e2020GL090037.
(10) Wu, S.; Zhou, W.; Xiong, X.; Burr, G. S.; Cheng, P.; Wang, P.; Niu, Z.; Hou, Y. The impact of COVID-19 lockdown on atmospheric CO2 in Xi’an, China. Environ. Res. 2021, 197, No. 111208.
(11) Volasco, E. Impact of Singapore’s COVID-19 confinement on atmospheric CO2 fluxes at neighborhood scale. Urban Clim. 2021, 37, No. 100822.  
(12) Yadav, V.; Ghosh, S.; Mueller, K.; Karion, A.; Roest, G.; Goudjdi, S. M.; Lopez-Coto, I.; Gurney, K. R.; Parazoo, N.; Verhulst, K. R.; Kim, J.; Prinzivalli, S.; Fain, C.; Neuhorn, T.; Mountain, M.; Keeling, R. F.; Weiss, R. F.; Duren, R.; Miller, C. E.; Whetstone, J. The Impact of COVID-19 on CO2 Emissions in the Los Angeles and Washington DC/Baltimore Metropolitan area. Geophys. Res. Lett. 2021, 48, No. e2021GL092744.  
(13) Suess, H. E. Radiocarbon concentration in modern wood. Science 1955, 122, 414–417.  
(14) Tans, P. P.; De Jong, A. F.; Mook, W. G. Natural atmospheric 14C variation and the Suess effect. Nature 1979, 280, 826–828.  
(15) Levin, I.; Kromer, B.; Schmidt, M.; Sartorius, H. A novel approach for independent budgeting of fossil fuel CO2 over Europe by 14C observations. Geophys. Res. Lett. 2003, 30, No. 2194.  
(16) Reimer, P. J.; Austin, W. E. N.; Bard, E.; Bayliss, A.; Blackwell, P. G.; Bronk Ramsey, C.; Butzin, M.; Cheng, H.; Edwards, R. L.; Friedrich, M.; Grootes, P. M.; Guilderson, T. P.; Hajdas, I.; Heaton, T. J.; Hogg, A. G.; Hughen, K. A.; Kromer, B.; Manning, S. W.; Muscheler, R.; Palmer, J. G.; Pearson, C.; van der Plicht, J.; Reimer, R. W.; Richards, D. A.; Scott, E. M.; Southon, J. R.; Turney, C. S. M.; Wacker, L.; Adolphi, F.; Büntgen, U.; Capano, M.; Fahmi, S. M.; Fogtman-Schulz, A.; Friedrich, R.; Köhler, P.; Kudsk, S.; Miyake, F.; Olsen, J.; Reimig, F.; Sakamoto, M.; Sookdeo, A.; Talamo, S. The IntCal20 Northern hemisphere radiocarbon age calibration curve (0–55 CAL kBP). Radiocarbon 2020, 62, 725–757.  
(17) Hsueh, D. Y.; Krakauer, N. Y.; Randerson, J. T.; Xu, X.; Trumbore, S. E.; Southon, J. R. Regional patterns of radiocarbon and fossil fuel-derived CO2 in surface air across North America. Geophys. Res. Lett. 2007, 34, No. L02816.  
(18) Turnbull, J. C.; Keller, E. D.; Norris, M. W.; Wiltshire, R. M. Independent evaluation of point source fossil fuel CO2 emissions to better than 10%. Proc. Natl. Acad. Sci. 2016, 113, 10287−10291.  
(19) Palstra, S. W. L.; Karstens, U.; Steurman, H.-J.; Meijer, H. A. J. Wine ethanol 14C as a tracer for fossil fuel CO2 emissions in Europe: Measurements and model comparison. J. Geophys. Res. 2008, 113, No. D21305.  
(20) Shibata, S.; Kawano, E.; Nakabayashi, T. Atmospheric [14C]CO2 variations in Japan during 1982–1999 based on 14C measurements of rice grains. Appl. Radiat. Isot. 2005, 63, 285–290.  
(21) Bozhinova, D.; Combe, M.; Palstra, S. W. L.; Meijer, H. A. J.; Krol, M. C.; Peters, W. The importance of crop growth modeling to interpret the 14CO2 signature of annual plants. Global Biogeochem. Cycles 2013, 27, 792–803.  
(22) Turnbull, J. C.; Miller, J. B.; Lehman, S. J.; Tans, P. P.; Sparks, R. J.; Southon, J. R. Comparison of 14CO2, CO and SF6 as tracers for determination of recently added fossil fuel CO2 in the atmosphere and implications for biological CO2 exchange. Geophys. Res. Lett. 2006, 33, No. L01817.  
(23) Turnbull, J. C.; Mikaloff Fletcher, S. E.; Ansell, J.; Brailsford, G. W.; Moss, R. C.; Norris, M. W.; Steinkamp, K. Sixty years of radiocarbon dioxide measurements at Wellington, New Zealand: 1954–2014. Atmos. Chem. Phys. 2017, 17, 14771–14784.  
(24) Flesch, T. K.; Wilson, J. D.; Harper, L.; Crenna, B.; Sharpe, R. Deducing ground-to-air emissions from observed trace gas concentrations: A field trial. J. Appl. Meteorol. 2004, 43, 487–502.  
(25) Xie, S. Auckland’s Greenhouse Gas Inventory to 2015; ISSN 2230-4525 (Print) ISSN 2230-4533 (Online) ISBN 978-1-98-852960-8 (Print) ISBN 978-1-98-852961-5 (PDF); Auckland Council, 2017.  
(26) Dortans, C.; Anderson, B.; Stephenson, J.; Jack, M. Estimating the Technical Potential of Residential Demand Response in New Zealand: A Summary of Results; GREENGrid Project Report, 2018.  
(27) Marley, H. G.; Dirks, K. N.; McKendry, I.; Weisett, L. F.; Salmon, J. A. A Ceilometer-Derived Climatology of the Convective Boundary Layer Over a Southern Hemisphere Subtropical City. Boundary-Layer Meteorol. 2021, 178, 435–462.  
(28) Patel, H.; Talbot, N.; Salmond, J.; Dirks, K.; Xie, S.; Davy, P. Implications for air quality management of changes in air quality during lockdown in Auckland (New Zealand) in response to the 2020 SARS-CoV-2 epidemic. Sci. Total Environ. 2020, 746, No. 141129.  
(29) Gensheimer, J.; Turner, A. J.; Shekhar, A.; Wenzel, A.; Keutsch, F. N.; Chen, J. What are different measures of mobility telling us about surface transportation CO2 emissions during the COVID-19 pandemic? J. Geophys. Res.: Atmos. 2021, 126, No. e2021JD034664.