A novel method to estimate emissions reductions of mobility restriction: the case of the COVID-19 pandemic

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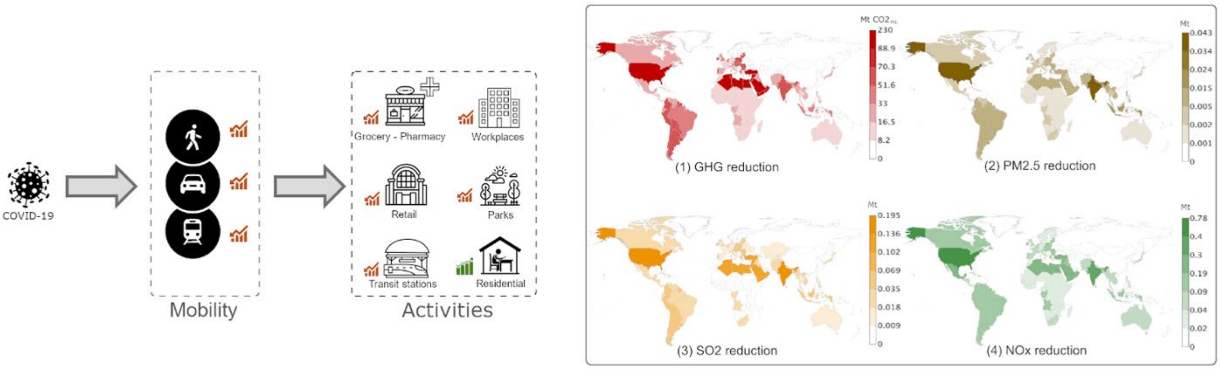

Abstract

The COVID-19 pandemic is the single largest event in contemporary history for global mobility restriction, with the majority of the world population experiencing various forms of 'lockdown'. This phenomenon incurred increased teleworking and time spent at home, fewer trips to shops, closure of retail outlets selling non-essential goods, and near-disappearance of leisure and recreational activities. This paper presents a novel method for an economy-wide estimate of the emissions reductions caused by the restriction of movement. Using a global multi-regional macro-economic model complemented by Google Community Mobility Reports (CMR) and national transport data, we cover 129 individual countries and quantify direct and indirect global emissions reductions of greenhouse gases (GHG; 1,173 Mt), $PM_{2.5}$ (0.23 Mt), SO_2 (1.57 Mt) and NO_x (3.69 Mt). A statistically significant correlation is observed between cross-country emission reductions and the stringency of mobility restriction policies. Due to the aggregated nature of the CMRs we develop different scenarios linked to consumption, work, and lifestyle aspects. Global reductions are in the order of 1-3% (GHG), 1-2% ($PM_{2.5}$), 0.5-2.8% (SO_2), and 3-4% (NO_x). Our results can help support crucial decision-making in the post-COVID world, with quantified information on how direct and indirect consequences of mobility changes benefit the environment.

Introduction

The COVID-19 pandemic, caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)[1], has brought the world to a standstill. It started in the Chinese city of Wuhan at the end of 2019 and quickly spread worldwide. By June 16 2020, there were more than 8 million cases globally, with the United States and parts of Europe the worst affected and Latin America as the new epicentre of the pandemic[2]. Five months later, cases exceed 50 million, with a second wave in many countries. Governments around the world have implemented a wide range of policies and restrictions for slowing the spread of the virus[3]. At least 93% of the world population resides in countries with restrictions in place and over 3 billion people are under permanent border closures[4, 5]. A tool developed by the University of Oxford (OxCGRT) measures the 'stringency' of policies across a range of indicators referring to containment and closure (e.g. school and workplace closures, travel bans), calculated in the form of a 'Stringency Index'. OxCGRT reveals the full extent of restrictions placed on the world population[6], and thus demonstrates the evident effect of the COVID-19 pandemic on global mobility.

The pandemic impacted all aspects of human life; businesses have been forced to cease their operations or transition to teleworking[7]. More than half of the world's population has been put into various forms of 'lockdowns', allowing only 'essential' travel, such as for buying grocery and pharmaceutical items. People have therefore been travelling less and spending more time at home.

Such changes in mobility produced an observable effect on the environment. One of the first changes was documented for Wuhan. Maps produced by NASA[8] show evident reductions in the concentration of nitrogen dioxide (a gas emitted from burning of fossil fuels), highlighting the potential causal link between COVID-19 and the subsequent reduction in the use of public and private transport due to quarantine measures, and therefore a decline in harmful air pollutants[9]. This effect has been seen in other countries too[10-12]. There have also been counter-arguments provided for the reduction in emissions, implying that drops in anthropogenic emissions in China did not avoid severe air pollution[13].

For understanding trends in mobility in response to measures aimed at combating COVID-19, Google released Community Mobility Reports[14] (CMR), showing mobility changes across a range of six categories: retail and recreation, groceries and pharmacies, parks, transit stations, workplaces and residential. Here, for the first time, we integrate such information on personal mobility with a comprehensive multi-regional input-output (MRIO) database for the global economy to offer a novel method that accounts for the wide-ranging regional and sectoral spill-over effects of emissions reductions resulting from limiting people's movement. We focus on the period extending through to the end of May 2020 since several countries opened up their borders again in June with forms of mobility and international travel resuming. Existing emissions reductions estimates do exist but either cover single countries (e.g. China[15] or Italy[16]) and cities[17], or rely on simplified modelling and do not take into account economy-wide global implications[18]. Also, unlike other ongoing work[19] based on Google CMR—which does not use input-output analysis, utilises European averages to represent multiple countries and assumes Google data to represent full traffic volume reductions—we utilise primary data on modal transport shares and car shares for 129 individual countries, and develop a range of scenarios with aspects linked to consumption, work, and lifestyle choices to account for the inherent uncertainty caused by the aggregated nature of CMRs.

The following section describes the data and methods we used, and it is followed by key results and their discussion. Extensive information on methodological details, uncertainty and limitations, and the full set of results are available in the supplementary information (SI) linked to this article.

Materials and Methods

To unpack the aggregated nature of Google CMRs, we develop 12 scenarios aiming to capture variations in consumption (S1 – S6), work (S7, S8), and lifestyle patterns (S9, S10), and combinations of these three key elements (S11, S12) (Figure 1).

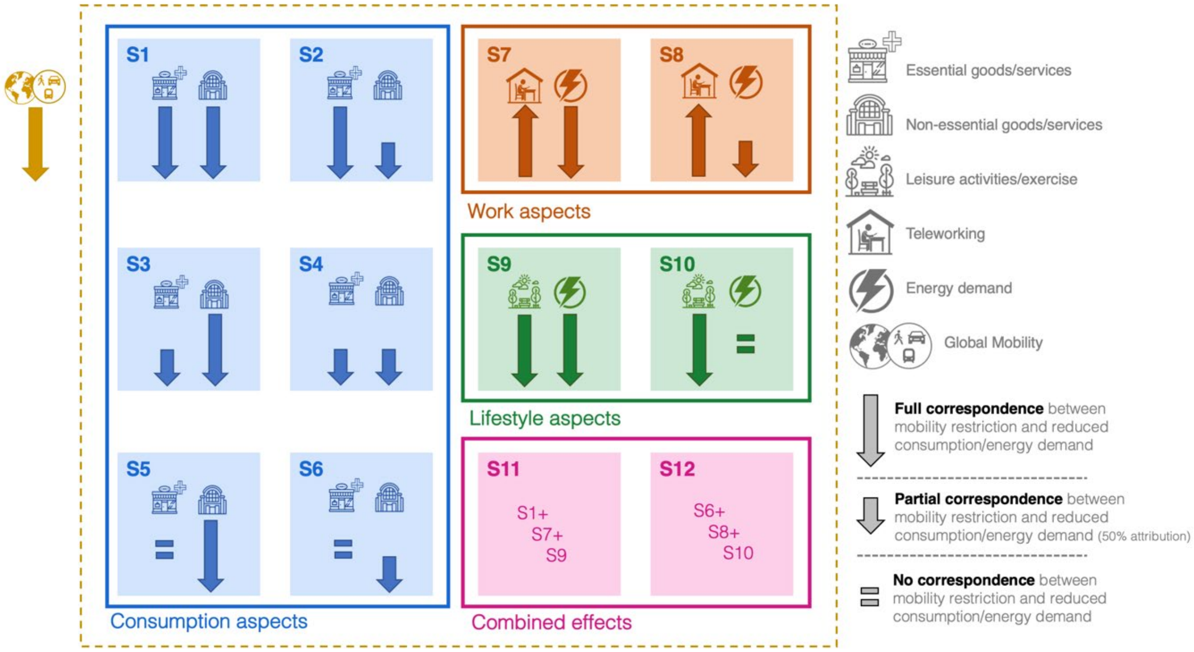

Figure 1- Scenarios developed to capture potential consequences of mobility restriction. All scenarios apply to all countries and regions we considered (Table S1, left column), and extend over the same time period (SI2). S1-S6 deal with consumption aspects, where different combinations of how reduced mobility might influence reduced consumption are provided for both essential and non-essential goods and services. S7 and S8 deal with potential reduced energy demand linked to increased teleworking. S9 and S10 cover aspects linked to lifestyle, in the form of the 'carbon-intensity' of leisure activities and exercise. In S10 these are considered 'carbon-free', whereas in the other there is full correspondence between the two. S11 and S12 capture the combined effects of consumption, work, and lifestyle aspects. Some scenarios are potentially unlikely (e.g. S2) but we opted for a broad approach to cover possible cases. The only option not considered is where demand for non-essential goods and service does not vary as this is impossible due to global closure of shops, restaurants and retail outlets and the already announced global recession.

These 12 scenarios are then combined with two allocation methods (attribution by GDP and attribution by population for countries covered as part of larger regions – see SI1 and SI2). Our approach combines novel mobility and transport data with established methods for ecological economics modelling. The three main elements behind the results shown in this paper are detailed in the following sections.

MRIO analysis

To capture the supply-chain effects of mobility restrictions, we use multi-region input-output (MRIO) analysis[20]. MRIO analysis, conceived by Nobel prize Laureate Wassily Leontief[21], has been applied to carbon emissions, biodiversity loss, air pollution, and public health[22, 23]. Also, as an important impact assessment method, it has been included in United Nations standards[24]. Global MRIO uses an $N \times N$ intermediate demand matrix $\mathbf{T}$, which links economic sectors as suppliers and users of commodities. This intermediate demand is added to final demand $\mathbf{y}$, to determine the total output $\mathbf{x}$, which yields the fundamental identity of input-output accounting $\mathbf{x} = \mathbf{T1} + \mathbf{y}$, where the vector $\mathbf{1} = \{1,1,\ldots,1\}$ is a summation operator. Global production can be described by the technical coefficient matrix $\mathbf{A} \coloneqq \mathbf{T}\hat{\mathbf{x}}^{-1}$, where the hat symbol denotes vector diagonalization. The $\mathbf{A}$ matrix captures direct supplier relationships but entire supply chains can be evaluated by using Leontief's inverse $(\mathbf{I}-\mathbf{A})^{-1}$. Therefore, the total output can be expressed as $\mathbf{x}=\mathbf{T}\hat{\mathbf{x}}^{-1}+\mathbf{y} \Leftrightarrow \mathbf{x}=(\mathbf{I}-\mathbf{A})^{-1}\mathbf{y}$, where $\mathbf{I}$ is an identity matrix[25].

To assess the economic impacts of mobility restrictions, we use disaster impact analysis[26], a branch of input-output analysis. This method determines post-disaster consumption scenarios by using an event matrix, $\mathbf{\Gamma}$, where the relative loss of industries as a direct result of a disaster is described by the elements Γ_{ii}, where i=1,…,N. We apply a quadratic programming algorithm to the constrained optimisation of post-disaster total output and final demand. More specifically, we carry out the following optimisation[27]:

$$\text{Min} \sum_i (\tilde{x}_i - x_i)^2, \text{ subject to } \tilde{\mathbf{x}} \le (\mathbf{I}-\mathbf{\Gamma})\mathbf{x} \text{ and } \tilde{\mathbf{y}} = (\mathbf{I}-\mathbf{A})\tilde{\mathbf{x}} \ge \mathbf{y}_{\mathrm{St}},$$

where $\mathbf{x}$ is the pre-disaster output, and $\mathbf{y}_{\mathrm{St}} < 0$ are stocks that are able to satisfy final demand despite production shortages. This optimisation problem is solved to give $\tilde{\mathbf{y}}$, which defines the post-disaster consumption possibilities. Post-disaster, sectors and regions that are directly affected by mobility restrictions will experience reductions in consumption, as well as other areas of the global economy.

For the final step in determining the supply-chain effects of mobility restrictions, we use reductions in post-disaster consumption $\tilde{\mathbf{y}}-\mathbf{y}$, to determine reductions in emissions of greenhouse gases and air pollutants F, by connecting a satellite account $\mathbf{Q}$ to the Leontief inverse. Essentially, the difference $\tilde{\mathbf{y}}-\mathbf{y}$ is applied as a stressor to Leontief's generalised input-output calculus, according to relationship $F=\mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I}-\mathbf{A})^{-1}(\tilde{\mathbf{y}}-\mathbf{y})$.[28]

The Global MRIO Lab[29] was used to compile MRIO data ($\mathbf{x}, \mathbf{T}, \mathbf{y}, \mathbf{A}, \mathbf{y}_{\mathrm{St}}$) for 38 regions, each with 26 sectors (SI1). The following section describes how the event matrix $\mathbf{\Gamma}$ is populated.

COVID-19 Mobility Data & Scenario modelling

Google CMRs represent an unprecedented dataset[14] to track variations in mobility globally. Data shows how frequency of visits and length of stays change at key different places. The change is measured against a baseline (the 5-week period Jan 3–Feb 6, 2020) and data is made available on an ongoing basis from Feb, 15 2020. To capture the first 'global lockdown' we run analyses with the update released on June, 3 2020, which includes data through to May, 29 2020. By definition a reduction observed in a CMR can mean both fewer as well as shorter visits to a place. The first would have a beneficial effect in terms of emissions reduction from transportation while the second would not, nor would it represent a reduction in traffic volume because it is the visit to a shop that is shorter, and not the return trip. Similarly, shorter or fewer visits do not necessarily incur reduced spending at the place visited, with well-known global news on stockpiling in many countries[37, 38]. For these reasons, straightforwardly assuming that CMRs can be translated into traffic volume reduction and consumption losses would be misleading. Therefore, the 12 scenarios developed for this article aim at interpreting differently the aggregated reductions reported in the Google CMRs. Full details on assumptions and details used to populate the $\mathbf{\Gamma}$ matrix are given in SI2.

Transport-related Data

Google data tells us the extent of people's movement, but it reveals nothing about how they move. We have already discussed that plainly assuming Google mobility reduction as a reduction of traffic volume would be too simplistic an assumption and mislead results. By definition Google covers ‘community’ travel therefore inter-regional transportation and international travel is excluded. To meaningfully complement Google data, we tapped into transport data on both modal shares and car shares. Modal share constitutes an indicator that quantifies the percentage share of each specific transport mode (e.g. cars vs. public transport) within the transport network of a well-defined spatial entity (e.g. a country). While useful, modal shares do not offer information about the composition of the available vehicle fleet by transport mode. The car share indicator (i.e. total number of cars as a share of total vehicles) addresses this issue.

Both modal and car shares are indicators that vary greatly across the planet reflecting changes in culture, geography, distances, topology, wealth and many other features belonging to the socio-economic-demographic spheres[39, 40]. We use a novel global dataset that contains both modal and vehicle shares[41]. Modal share is used in this study to correctly assign an estimate in mobility reduction to the two main available modes of transport (private cars and public transport) so that corresponding reductions in emissions can be captured. Car share is instead used to correctly proportionate reduction in liquid fuels usage in various countries because even with car travel nearly fully halted by lockdowns other vehicles such as vans, trucks and buses are still running, thus requiring only the car fraction of liquid fuels usage to be reduced. Full details on how these two indicators are used and their values are given in SI2 and SI3 respectively.

Results and Discussion

With mobility restrictions, Google CMRs demonstrate how people respond to, and are willing to trade on, health concerns and different aspects of life. We translate this valuable *‘live’* behavioural data into reduced consumption patterns in order to estimate emissions reduction (Figure 2).

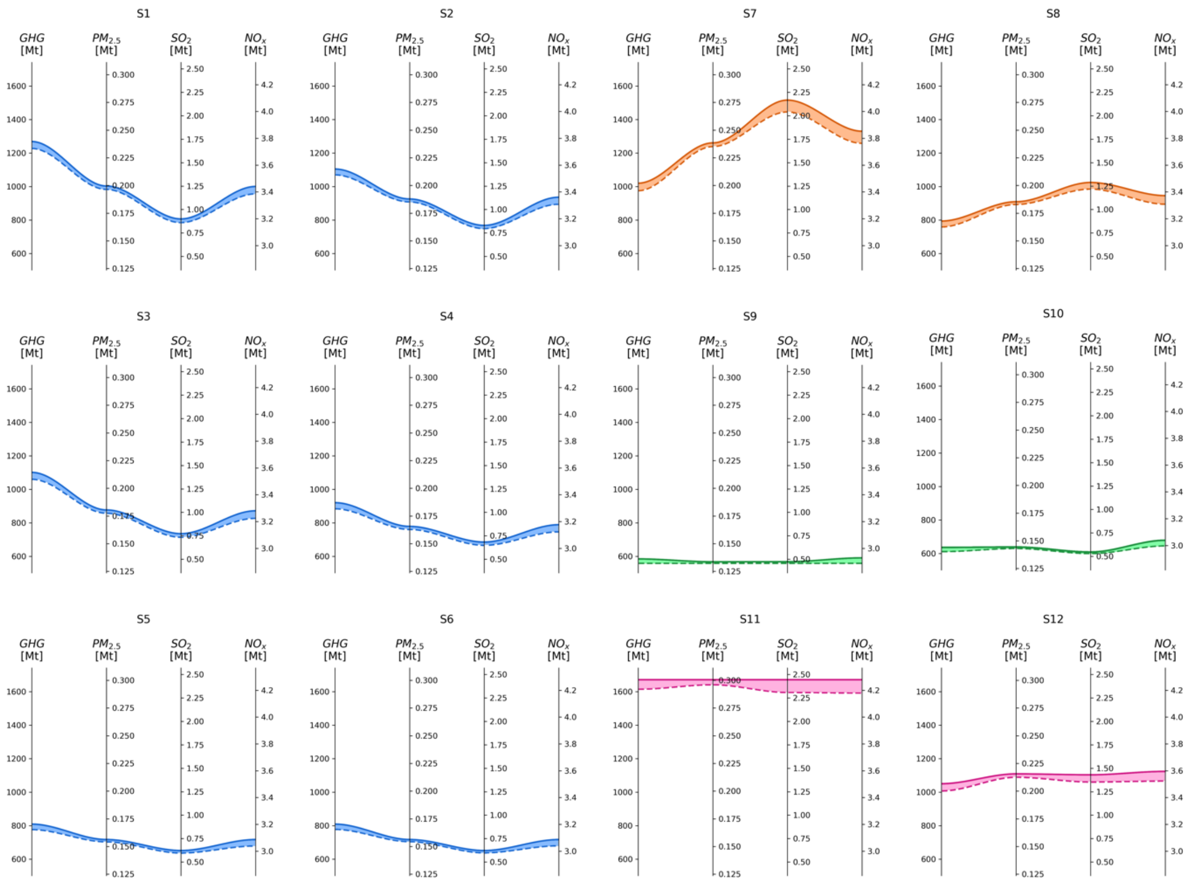

Figure 2 – Parallel coordinate plots for the 12 scenarios analysed reporting absolute [Mt] reduction for GHG, $PM_{2.5}$, SO_2, and NO_X. Each scenario is evaluated based on either GDP attribution (continuous line) or population attribution (dashed line), thus producing 24 sets of results. Shaded areas represent the marginal variation in results that can be obtained with either attribution method. Scenario results are linked to, and colour coded as, the scenarios defined in Figure 1: S1-S6 deal with consumption aspects, S7-S8 deal with work aspects, S9-S19 deal with lifestyle aspects, and S11-12 evaluate the effects of these three aspects combined. It can be seen that the two attribution methods used (either by GDP of a country as a share of the GDP of the region it belongs to or by the country's population as a share of the region's population) despite being substantially different have minimal influence on the results. This suggests a good robustness of our results.

Scenario 1 to 6 are designed to address emissions savings associated with people's consumption aspect on essential (e.g., food and pharmacy) and non-essential services (restaurants, theme parks, shopping centres); Scenario 7 and 8: work aspect (workplace and residences); Scenario 9 and 10: lifestyle aspects on daily outdoor activities (e.g., parks, gardens and public beaches). In all scenarios we also include as baseline reduced car travel, calculated as explained in SI2. Such reduction in emissions is conveniently singled out in S10, which assumes leisure activities to be 'carbon-free', therefore showing solely the effects of reduced private mobility. Lastly, Scenario 11 presents an upper bound by combing the maximum emissions reduction across these three elements, and Scenario 12 indicates the lower bound.

Maximum global reductions observed against a 2019 baseline fare at 3.04% (GHG), 2.12% ($PM_{2.5}$), 2.82% (SO_2), and 4.19% (NO_x). Given we focus on mobility only, and the fact that Google data is unavailable for two key global players (China and Russia) our results align well with existing studies which estimated global GHG reductions caused by COVID-19 to be in the region of 4-7%[18, 42]. Averaging across Scenario 11 and 12, the lockdowns over the 3.5-month (Feb 15th to May 29th) that we cover across 129 countries reduce global GHG emissions by 1,337.5 Mt (2.43%), NO_x 3.90 Mt (4.19%), SO_2 1.89 Mt (2.18%), and $PM_{2.5}$ 0.26 Mt (1.81%) from the baseline of 2019. Comparison of our results with those of other studies should be carried out cautiously when there are significant differences in data sources, methodological approach, time horizon, emissions covered, system boundaries, and units used.

By comparing the average against each scenario, we are able to identify the marginal benefits to the environment by changing different elements of our lifestyle. Reducing expenditure on purchasing goods and services (results in blue) create a significant effect in reducing emissions, with a maximum of 1,269 Mt of GHG saved (Figure 2, Figure S3a in SI4), half of which boils down to reduced transportation (635.38 Mt of GHG saved, Figure 1, S10). In contrast, the increase of teleworking (results in orange) allows the emissions of NO_x, SO_2, and $PM_{2.5}$ to be reduced in a relatively significant manner, due to the reduced energy use at working places. Especially, the reduction on SO_2 in teleworking is twice the effect of those resulting from the decreased consumption on everyday purchases. The reduction of park visits (results in green) in general produces a smaller environmental benefit globally as this activity does not lead to much emissions in the first place. This can be seen by the negligible difference produced by either full attribution (Figure 1, S9) or 'carbon-neutrality' (Figure 1, S10) of such leisure activities.

Absolute reductions are led by the USA, followed by India, Brazil, Indonesia, and the UK (SI4). Such reductions are, not surprisingly, intimately linked to the critical mass of country's total air pollution but also to how stringent measures are. We tested for the significance of the stringency index on the four pollutants covered in our analysis (SI6) and found it to be statistically significant across all. We built 34 linear regression models in the software NLOGIT with the stringency index as independent variable and emissions reductions (either as absolute values or logarithmic values) as dependent variables. We used a weighted least squares approach to tackle heteroscedasticity that may be present in the data, considering different weighting factors, such as GDP, population, and other exploratory weights linked to Google data (SI6). Figure 3 shows predicted and observed values for the four best models with full details of the other models we tested given in SI6.

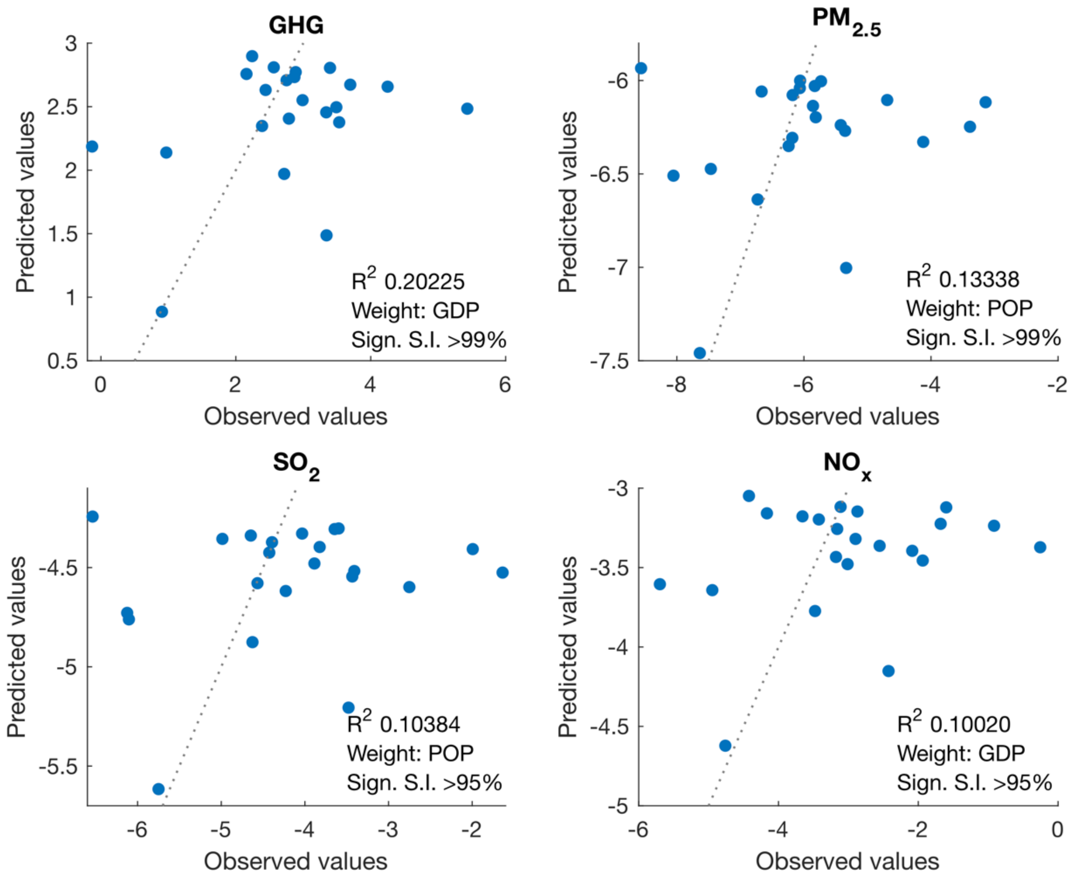

Figure 3 – predicted and observed values of emissions reduction for GHG, $PM_{2.5}$, SO_2, and NO_x. In all cases, the Stringency Index (S.I.) is statistically significant (with a confidence level of either >95% or >99%). The weighting factors for the best models are population (POP) for SO_2 and $PM_{2.5}$ and (GDP) for GHG and NO_x. Data points refer to individual countries in our analysis for which both Google Community Mobility Report data and Stringency Index were available at 29/05/2020 (n=22).

A simple, single variable such as the stringency index cannot be expected to capture the full complexity of the phenomenon we are studying. This is why there are differences observed within a same stringency index (e.g. 80, Figure S9) where some countries are able to manage a higher emission reduction rate (such as Spain, Singapore, and United Arab Emirates) than others. This is likely to be dependent on a country's economic structure, for emission intensive industries in a specific country may not be related to mobility. For instance, in a service-oriented city-state like Singapore, where most people commute by train, a lockdown would not lead to a reduction in car emissions and having them work from home would not affect service industries that much. Also, there could be signs of behavioural changes whereby people respond partially independently of, and in some cases more strongly than, governments guidance due to the perceived threat posed by the coronavirus. Such collective responses reflect government powers to enforce measures[43, 44] but interestingly also a civil society's capacity to decide wisely on its own. This gives hope for equally strong behavioural changes if the wider society embraces the idea that climate change is as real and global a threat as COVID-19 is.

A key sustainability question is to identify changes to our mobility patterns during the pandemic that may result in a permanent change in behaviour and energy use[45]. By testing consumption reduction in each category in the Google CMRs, this study sheds light on the way forward. Especially, teleworking, among others, exhibits the greatest potential. The unusual and rapid switch of COVID-19 enabled significantly higher percentage of teleworking. Google CMRs indicated that globally, visits/lengths of stay to working places reduced on average by 24.4% while people's time at home increased 11%. Besides the reduced commuting travel, the net energy saving for the substitution of working from office to home is positive. Even based on our conservative assumption that full mobility restrictions only translate into a 50% reduction of utility costs at offices, Scenario 8 indicates an environmental benefit of 793 Mt of GHG emissions reduction, and significant reduction in SO_2 (2.17 Mt), NO_x (3.85 Mt), and $PM_{2.5}$ (0.19 Mt) over a 3.5-month period. Extended over a year this translates into a GHG reduction of ~2,700 Mt (or 5% of global GHG emissions), which is half of the 9-10% decrease required every year between 2020-2050 in order to limit global warming to 1.5ºC without the use of technology that removes carbon dioxide from the atmosphere[46].

While nobody wishes to live in lockdown, among all mobility-related changes, teleworking and reduced work-related travel seem to offer the most feasible and long-lasting practice to sustainably change our society. Its potential is observed for both developed and developing economies which have achieved more than 40% reduction in visit/length of stay to working places. These records are much higher than the teleworking penetration rate before COVID-19 (< 5%)[47]. The combined effort to expand the information and communication technologies[48] and the support of institutions to their staff to work from home in a post-pandemic era would greatly assist the transition of our working styles as well as maintain the environmental benefit of reducing emissions. Perhaps ironically, the decreased mobility has assisted in tackling the negative impacts of travel and population clusters on the environment, likening the world to a seesaw, where losses on one side result in gains on the other. In Venice, water quality in canals drastically improved, with wildlife returning to the city whilst in India, reduced traffic pollution allowed the Himalayas to be viewed from hundreds of kilometers away. In the larger scheme of things, the COVID-19 pandemic will help shed light on the importance of a better balance between both sides in the generations to come.

Authors contribution

F.P., Y.-Y.S. and M.L. conceptualised the paper; F.P., My.L., B.D'A., and M.L.A. worked on the coding behind the results; F.P. and Y.-Y.S. planned and coordinated the data collection; F.P., Y.-Y.S., M.L., My.L., B.D'A., G.F., O.A.-G., M.L.A. and A.M. collected and processed data; F.P., Y.-Y.S., A.M., and M.L. wrote the paper; F.P., M.L., Y.-Y.S., and My.L. wrote the SI.

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