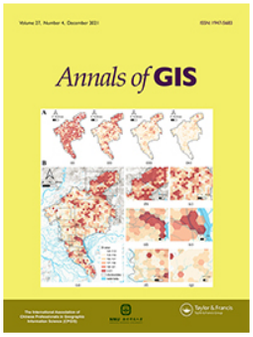

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Examining second-order impacts of COVID-19 in urban areas

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ABSTRACT

This paper examines the current state of knowledge focusing on the second-order impacts of the COVID-19 pandemic through a geospatial lens. The purpose is twofold: (1) present a global programme – Cities' COVID Mitigation Mapping (C2M2) programme – focusing on urban areas that explores second-order impacts through the use of geospatial tools and technologies, and (2) identify and assess the emerging literature on second-order impacts using geospatial data and analysis to support this project. Effects of the pandemic are rapidly unfolding across the world; however, an assessment of the literature reveals that second-order impacts of COVID-19 are seasonal, spatial, and scalar across multiple thematic areas includ-ing the economy, environmental health sector, education, and migration/mobility. Successive waves of the pandemic are continuing to be met with specific public health measures (e.g. lockdowns, travel restrictions, social distancing guidance, mandates for the use of personal protective equipment) that will have long-term impacts on vulnerable populations. A literature review was conducted to identify how the pandemic's second-order impacts derived from geospatial data and analysis can provide the basis for using geospatial data to study vulnerable urban populations more generally. This review reveals a gap in the literature, with far more articles emphasizing geospatial approaches to assess first-order impacts and alimited number of articles focused on geospatial approaches investigating second-order impacts. Nonetheless, this nascent literature provides the basis for designing approaches with local partners and by local and regional governments to apply geospatial data and methodologies to the development of mitigation strategies to prioritize limited resources to minimize the long-term consequences of COVID-19.

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Introduction

In early 2020, the outbreak of the novel coronavirus (SARS-CoV-2) and resulting illness, COVID-19, in Wuhan, China rapidly expanded across the globe. A highly contagious disease, the rapid transmission of the virus resulted in immediate first-order impacts, which include increasing numbers of cases and case fatalities, stressing hospital capacity, and generating government responses in the form of border restrictions, lockdowns, quarantines, and public health guidance. The World Health Organization declared this rapidly spreading coronavirus outbreak a pandemic on 11 March 2020 (Cucinotta and Vanelli 2020), and the worldwide scale of second-order impacts soon became evident, including a global economic crisis impacting all aspects of society, exacerbating chronic conditions of food insecurity, limited access to health services, and loss of livelihoods. This pandemic crisis magnifies fundamental inequities that require measures to plan for and adapt to the longer-term impacts of COVID-19. These implications highlight the need to generate robust data to track the virus, identify vulnerable populations, and monitor mitigation plans that integrate information from diverse sources and multiple scales.

Second-order impacts have specific repercussions and tangible outcomes that stem from human responses to the pandemic, rather than from the virus itself. For example, governmental lockdowns and the closure of businesses resulted in job losses, the inability to pay rent, evictions, and in some cases migration to other villages, cities, or countries. Examining second-order impacts from different disciplinary perspectives reveals many terms such as downstream effects, indirect effects, rebound effects, secondary effects, cascading effects, and ripple effects (Rivera et al. 2014) that point to the complex and long-term nature of these impacts. Some researchers refer to the negative impacts of extreme events, such as the COVID-19 pandemic as 'second-order disasters' (Madianou 2020, 2), or the adverse effects of human decisions in response to a calamity.

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The rapid pace of societal and economic change, particularly in developing urban environments, requires accelerated approaches to identify solutions and implement mitigation strategies in order to minimize the negative consequences of the pandemic's second-order impacts. Furthermore, second-order impacts expose and exacerbate existing inequities embedded in informal economies, patterns of mobility and migration, and access to basic services in informal settlements.

The pandemic reflects a complex pattern of uncertainty and vulnerability where the virus defies generalities, manifesting itself differently in different places while starkly revealing the spatial inequities across the globe (Beech et al. 2020). Urban areas host 60% of the world's population where in the months of June and July 2020, 90% of all reported COVID-19 cases occurred (UN-Habitat 2020). However, during the fall months of September, October, and November 2020 there was a surge in rural rates in the U.S., India, and Africa (USDA Economic Research Service 2020; Singh and Gettleman 2020; Ahenda 2020). Still, greater urban connectivity, dense social networks, and complex transportation systems increase the risk of the transmission of the virus in urban areas, where second-order impacts of the COVID-19 pandemic have been acutely felt (Teller 2021). In low- and middle-income countries (LMICs), these effects are intensified in cities with vulnerable populations who are already affected by poverty, live in informal or peri-urban areas, and struggle to meet basic needs (Wilkinson 2020). Societal factors also influence susceptibility to the disease. Examining those conditions that include malnutrition, hazardous working conditions, stressed supply chains, and inadequate public programmes are necessary as the numbers of vulnerable people increase (Frey 2020; Yong 2020). Understanding these urban trends will inform efforts to address similar issues in rural areas.

Geography is central to the COVID-19 story and the underlying science as the pandemic crosses boundaries, scales, and cultures. The purpose of this paper is twofold: (1) to introduce a global programme – the Cities' COVID Mitigation Mapping (C2M2) programme – focusing on urban areas in lower income countries to address local second-order impacts by applying geospatial tools and technology and (2) to examine the emerging literature that examines second-order impacts based on geospatial data and analysis that can inform this project. The COVID-19 pandemic has facilitated and accelerated scientific research across multiple disciplines yielding rich array of scientific results and findings. Indeed, there are numerous articles on first-order impacts using geospatial approaches that track the spread of the virus, examine transmission rates, and map death rates (Ahasan et al. 2020). Although there have been hundreds of published articles focusing on the numerous second-order impacts of the COVID-19 pandemic in 2020 and 2021, the literature reviewed here is related to the impacts in cities in LMICs that are the focus of the C2M2 programme. These impacts were identified by project teams as critical to their cities, and they include economy, environmental health, education, and migration/mobility. Since the second-order impacts of COVID-19 are seasonal, spatial, and scalar across multiple sectors of society, geospatial approaches to research these impacts can be useful to policy makers and inform their efforts to mitigate their negative effects. However, we find that the emerging literature on applications of geospatial approaches to second-order impacts is limited; robust data are needed for analysing second-order impacts, and demonstration projects that apply these data, such as the C2M2 programme, are needed to assist with developing mitigation strategies.

Geospatial approaches to second-order impacts

Many questions related to the current pandemic are geographic in nature. Dynamic, interactive maps can help other sciences better understand its roots, its spread, and ultimately its management (e.g. Boulos and Geraghty 2020; Kim et al. 2021; Kim and Kwan 2021; Smith and Mennis 2020; Yang et al. 2020). When informed by human geography data – demographic data about who lives where (i.e. gender, ethnicity, age, employment, mortality, education) and characteristics about health services, community facilities, transportation, and education – maps can provide insights into the social, economic, and political context of novel phenomena, including COVID-19. Using a geographic lens to interpret the data, while trying to better understand the nature of places behind the statistics, helps us find ways to see relationships between local and global scales.

The proliferation of interactive maps related to the first-order impacts of the pandemic is an important contribution towards better understanding the ongoing threat. Multiple data dashboards track global and country-specific statistics and cartographic visualizations of cases and deaths, most notably the Johns Hopkins University COVID-19 dashboard. These dashboards point to the importance of sharing and visualizing public data in the interests of public health.

While the COVID-19 virus has catalysed an international research effort to create a vaccine in record time (Yong 2020), it also provides an opportunity to facilitate global research using geospatial analyses (Ahasan et al.

2020; Fatima et al. 2021; Helbich, Browning, and Kwan 2021; Yang et al. 2020). Ahasan et al. (2020) conduct a systematic review of emerging research of geographic information systems (GIS) and geospatial analyses of COVID-19 across thematic groups with an emphasis on public health and first-order impacts (e.g. environment, socio-economic, health surveillance, spatial pattern analysis of COVID-19, and computer-aided spatial and statistical analysis and modelling). Yang et al. (2020) provide an overview of a spatiotemporal perspective and preliminary results from multiple research projects (i.e. human movement patterns during COVID-19, air quality changes in selected Chinese cities, impacts on the global stock market, and socio-economic impacts on vulnerable populations in the United States). The World Bank maintains the interactive COVID-19 High-Frequency Monitoring Dashboard, which provides a map and country-level data on 96 indicators in multiple topic areas such as the impacts of COVID-19 on education, health, incomes, labour, and safety nets (World Bank 2021). This dashboard allows users to compare how the impacts of COVID-19 vary across countries, over time, and by industry sector and regions. Additionally, Fatima et al. (2021) and Helbich, Browning, and Kwan (2021) argue that future COVID-19 geospatial research can benefit from using fine-scaled data to mitigate several methodological limitations (e.g. Modifiable Areal Unit Problem) that may result from using spatially aggregated data. Our literature review complements Ahasan et al. (2020) and Yang et al. (2020) by inspecting the geospatial approaches to examining second-order impacts of COVID-19 generally and to inform the C2M2 project specifically.

The Cities' COVID Mitigation Mapping (C2M2) program to track geospatial applications of second-order impacts

In response to the global pandemic the U.S. Department of State (DOS) and U.S. Agency for International Development (USAID) are using foreign assistance funds to implement many projects for emergency health, humanitarian, development, and economic assistance (https://www.state.gov/update-the-united-states-continues-to-lead-the-global-response-to-covid-19-6/). The DOS Office of the Geographer and Global Issues (GGI) is supporting these foreign assistance efforts to mitigate COVID-19 second-order impacts by establishing the C2M2 programme. The COVID-19 pandemic and associated second-order effects will likely lead to development backsliding and increased instability among vulnerable populations. The goal of the C2M2 programme is to expand local geospatial capacity in project communities while developing an understanding of

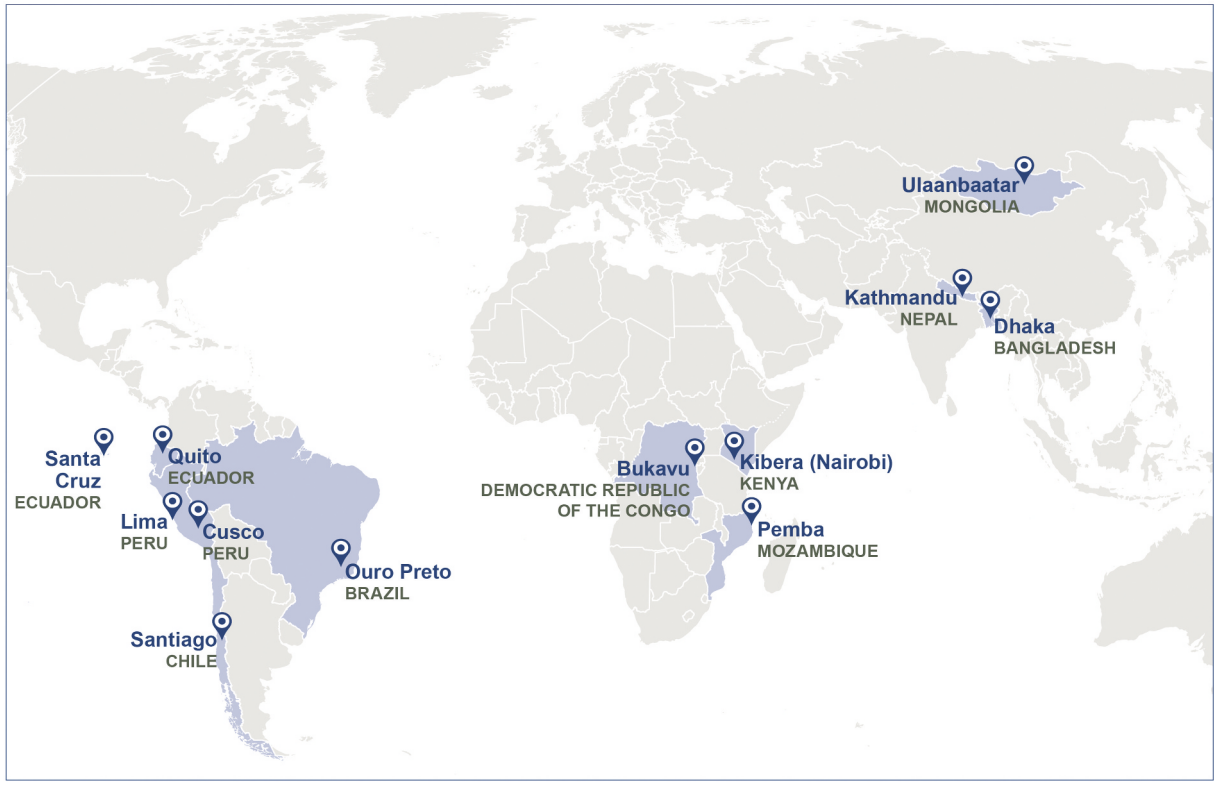

Figure 1. Location of Cities' COVID Mitigation Mapping projects (https://mapgive.state.gov/c2m2/).

Table 1. C2M2 Projects and Activities.

C2M2 Location	Regional Hub	C2M2 Project
Latin America	Mobility and migration	Quito, Ecuador Lima, Peru Santiago, Chile
	Consequences of the collapse of tourism economy	Santa Cruz, Galapagos, Ecuador Cuzco, Peru Ouro Preto, Brazil
Africa	Access to health services Tracking schools and student adaptations to COVID-19	Bukavu, Democratic Republic of Congo (DRC)
	Impacts on informal economy on vulnerable populations	Pemba, Mozambique
	Assess the impact on education sector	Nairobi, Kenya
Asia	Economic impact of government shutdown on tourism	Across the Asia Hub region, based out of Kathmandu Nepal
	Internal migration patterns	Dhaka, Bangladesh
	Access to health services in vulnerable neighbourhoods	Ulaanbaatar, Mongolia

Table 2. Literature review (115 articles accessed; August 2020 to February 2021).

Topic (# of articles)	Type (# of articles)	Region[a] (# of articles)
Economic Impacts (10) – Tourism (21) Environmental Health Impacts (16) – Health (11) – Food Security (13) Education Impacts (11) – Social Protection (8) Migration/Mobility Impacts (19) Information Impacts[b] (6)	Commentary (17) Dataset (7) Journal Article (65) Policy Brief (9) News Article (2) Research Report (10) Technical Note (5) Dashboard (1) Database (1) Journal Article (6) News Article (1) Policy Brief (4) Research Report (5) Technical Note (1) Commentary (3) Dataset (2) Journal Article (6) Policy Brief (3) Press Release (1) Research Report (2)	Global (43) Africa (13) Asia (33) Latin America (14) Europe (5) United States (7) Global (3) Africa (3) Asia (4) Europe (2) Latin America (6) Global (8) Asia (9)

[a]Articles by region address multiple topics; refer to MapGive C2M2 Resource tab.

[b]Information articles address specific data issues related to data sharing, privacy, ethics, and data management that are second order impacts beyond the scope of this paper.

NOTE: All articles define a second-order impact; 38 articles across multiple topics specifically apply geospatial approaches to a second-order impact.

their needs and resource gaps to enable data-driven decision-making to create strategies to mitigate these COVID-19 second-order impacts, in particular for vulnerable urban populations.

To accomplish the programme goal, C2M2 builds on regional networks of geospatial expertise to analyse second-order impacts of COVID-19. Geospatial analysis of rapidly growing cities in low- and middle-income countries provide options for scenarios and mitigation planning. City-level projects of the C2M2 programme buttress local capacity to utilize geospatial data and technologies, strengthen international partnerships, and create new data to fill information gaps and inform data-driven decision-making for policies that address COVID-19 second-order impacts. Building on the DOS GGI Secondary Cities (2 C) Initiative, the C2M2 programme selected from established partners to create three regional hubs encompassing Latin America, Africa, and Asia. Using their local knowledge, network, and regional awareness, hub leaders identified selected partner cities (Figure 1).

Each city undertook a baseline assessment of their city to determine second-order impacts of COVID-19. Using the partner's prioritization of second-order impacts allowed us to focus our literature review on the emerging research on key topics related to each city (Table 1). In addition, C2M2 partners assess existing data, create data on project topics, and conduct analysis, maps, and visualizations to inform policy decisions and mitigation strategies. Partners work with local communities and government to develop participatory methods in problem identification, data requirements, mapping, and project implementation. These projects reflect the outcomes of the literature review that inform the methodology for geospatial analyses conducted to track specific second-order impacts across the three regional hubs.

Literature review of COVID-19 second-order impacts to support C2M2 program

From August 2020 to February 2021, a literature review was undertaken focusing on geospatial approaches to second-order impacts of COVID-19 in urban areas. (MapGive C2M2 Resources tab). One hundred and fifteen articles were examined and organized by topic, type, and region. (Table 2). The review was conducted via online searches of academic journal articles and other literature using EBSCO, Google Scholar, JSTOR, Web of Science, PubMed, and other search engines with access to multidisciplinary and subject-specific databases. Preprints were not specifically searched, but they were not excluded; early citations (published online but not yet

assigned an issue) show up in publication databases. Search terms included *COVID-19, SARS-CoV-2*, and *coronavirus*, along with thematic phrases related to specific second-order impacts. We highlight the specific C2M2 themes of economy, environmental health, education, and migration/mobility. Our review identifies publications that define a second-order impact, identify geospatial approaches, and pinpoint gaps in this emerging literature where geospatial approaches may contribute to outcomes and solutions. Underlying the multiple social issues related to the pandemic is the need for information that is integrated across topics.

Journal articles, research reports, and commentary describe second-order impacts related to the economy that include remittances (Ratha et al. 2020), employment (Gentilini et al. 2020), inequality (UN-Habitat 2020), tourism (Gössling, Scott, and Hall 2021), and poverty (Martin et al., 2020). Several articles describe the impact of COVID-19 restrictions on air quality (described below); albeit there are other environmental impacts such as wildlife movement and behaviour (Rutz et al. 2020), water quality improvements (Mostafa, Gamal, and Wafiq 2021), increased use and disposal of solid waste (Kulkarni and Anantharama 2020; Sarkodie and Owusu 2020; Silva et al. 2021), and changing deforestation rates (NASA 2020). Themes categorized as society include social protection measures (Karaye and Horney 2020), education (Osman 2020; Tartavulea et al. 2020), food security (Crush and Si 2020; Ruszczyk et al. 2020), health (Ahuja, Shah, and Mohammed 2020; Idowu, Olawuyi, and Nwadioke 2020), and migration (or mobility) (Karim, Islam, and Talukder 2020; Li et al., 2020; Shakibaei et al. 2021; Truelove et al. 2020; Yi et al. 2020). Also, there are 38 articles utilizing a geospatial approach, such as spatial modelling (Karaye and Horney 2020), spatio-temporal studies (Yang et al. 2020), and surveys (UNHCR 2020). Visualizations include cartographic products, infographics (Africa Center for Strategic Studies 2020), and forecasting (Ratha et al. 2020).

Economic impacts

The review of literature on the economic impacts of the COVID-19 pandemic reveals negative impacts at both macroeconomic and microeconomic levels. Macroeconomic impacts include strains on government budgets, disruptions to labour markets, and overall declines in spending and economic growth. Some industries have suffered profound negative impacts, particularly in the tourism, hospitality, and entertainment sectors, which are directly affected by travel restrictions and mandated closures of restaurants, cinemas, museums, and performance venues. Microeconomic impacts include increased unemployment, poverty, and disruptions in meeting basic needs, including food, housing, utilities, and access to credit.

The economic impacts of the COVID-19 pandemic are likely to be most acutely felt in areas where tourism is a critical sector in the local economy. Tourism inherently involves the movement of people within and between countries. The global mobility associated with most forms of tourism has likely been a major contributing factor for the rapid spread of the virus (Gössling, Scott, and Hall 2021), and the widespread global travel restrictions that followed had negative economic consequences for the travel and tourism sector in most tourism destinations. Given the spatial nature of tourism, the most vulnerable tourism destinations are those with the greatest relative share of tourism in each local economy as determined by proportionate contribution to local gross domestic product. Rogerson and Rogerson (2020) use geospatial approaches to identify the most vulnerable tourism destinations in South Africa. They find that the effects of declining tourism and spending are experienced in the country's leading metropolitan areas, including the Cities of Johannesburg, Tshwane, Ekurhuleni, Cape Town, and eThekwini.

Qiu et al. (2020) assess the social costs of tourism in three urban destinations in China, namely Hong Kong, Guangzhou, and Wuhan. To assess the negative social impacts of tourism amidst a pandemic, they describe residents' perceptions of the risks posed by tourism activity and estimate their willingness to pay to reduce public health risks based on hypothetical scenarios, using the contingent valuation method. Findings suggest that residents of these three cities were willing to pay an average of approximately 46 USD to reduce the risk of negative tourism-generated pandemic effects, and that half of the population were willing to pay at least 30 USD for such preventative measures.

Tourism is one of the most important economic sectors in Nepal (Sah et al. 2020). The detection of COVID-19 cases in early 2020 was followed by cancellations of hotel and tourist bookings, which resulted in widespread unemployment, loss of income, and threatened livelihoods for thousands of Nepalese people. The collapse of international and domestic tourism and the related loss of tourism revenues have negatively affected national budgets and led to adverse financial impacts on households throughout the country (Sah et al. 2020).

Research on the economic impacts of the COVID-19 pandemic is dynamic and emerging rapidly as new information about the spread of the virus prompts responses at the government and household levels. Nevertheless, there remains a great deal of uncertainty in terms of the

effectiveness of these responses in mitigating the worst economic impacts. In addition, there is a gap in the literature to date regarding the spatial nature of these impacts that vary widely in location, scope, and scale. Few studies have used geospatial applications to examine the impacts of the COVID-19 pandemic on the tourism sector. Given the economic importance of this sector to cities and regions throughout the world generally and to the C2M2 programme in particular, there is a need for spatial analysis of where tourism impacts are emerging and over what time scale. An increase in the availability of data will likely lead to a greater understanding of the near- and long-term impacts on national and regional economies, and on communities and households, all of which are important components of the global economy.

Environmental health impacts

The review of literature on the environmental health impacts of the COVID-19 pandemic reveals both positive and negative effects, which are largely driven by changes in human behaviour in response to widespread lockdown measures and travel restrictions. The relationship between social factors such as health, food, environmental services, and social protection is based upon the underlying demographics. As this literature review expands with new contributions, identifying how data are used to cross-walk between various topics to create new information will be critical to tracking data-driven decision-making in how society adapts to the pandemic.

Second-order environmental health-related impacts of the COVID-19 pandemic in cities vary widely depending on (i) the scale of the outbreak of the virus, (ii) policy responses, and (iii) the environmental factors under examination. Socially vulnerable populations have increased health risks during disasters due to their inability to access adequate medical care, transportation, and nutrition (Karaye and Horney 2020).

Using spatial prediction methods, secondary spatial data on social vulnerability, and publicly available data on COVID-19 case counts, Karaye and Horney (2020) assess the association between the pandemic's case counts in the U.S. and the Center for Disease Control's Social Vulnerability Index. They identify hot spots where social vulnerability is positively associated with case counts. They note that large-scale disasters differentially affect the health of marginalized communities, and they find that minority status, language, household composition, transportation, and disability all predicted COVID-19 case counts in the U.S. The authors conclude that addressing the social factors that create poor health is essential to reducing inequities in the health impacts of disasters. This approach to vulnerability provides a framework for the C2M2 programme to conduct social vulnerability assessments across the suite of cities in lower and middle-income countries.

The dramatic increase in urban food insecurity from the COVID-19 pandemic is partly a function of the disruptions in national and globalized food supply chains that highlight concerns about food production, processing, distribution, and demand (Aday & Aday, 2020; Morton 2020). Crush and Si (2020) suggest that the number of severely food insecure people could more than double, from 130 million to 265 million, by the end of 2020. They note that the disruption to food systems has important implications for both the control of the epidemic and the current and future food security of urban households. Ruszczyk et al. (2020) conduct in-depth household surveys in two small cities in Bangladesh (Mongla and Noapara) to examine the COVID-19 pandemic's impact on food security during a period of lockdown. The findings reveal that households are using coping strategies including curtailing consumption of food, relying on inexpensive starchy staples, increasing the share of total expenditure allocated to food, taking out loans, and accessing relief from social protection programmes. The authors highlight the importance of relying on social capital and relationships with local governments for food insecurity coping strategies during the pandemic. Disruptions to food supply chains have exacerbated existing problems of food insecurity and malnutrition, and it is unclear how the economic actors in those supply chains will rebound to increase the availability of and access to food (Crush and Si 2020; Aday & Aday,2020).

Environmental outcomes due to the pandemic are directly related to health. Numerous case studies document improvements in air quality, particularly in cities, which are marked by a decrease in industrial activity and automobile travel. These improvements in air quality are also associated with a decline in greenhouse gas emissions in the short-term. Similarly, a decline in tourism activity in many popular destinations has corresponded with reduced noise pollution, litter, and surface water pollution. By contrast, some research has documented that changes in household consumption have generated greater volumes of packaging from shipments, household waste, personal protective equipment, and medical waste (Mostafa, Gamal, and Wafiq 2021; Sarkodie and Owusu 2020; Silva et al. 2021). In addition, the increase in municipal waste has created additional burden on solid waste disposal systems and recycling centres. (Kulkarni and Anantharama 2020; Silva et al. 2021).

Roy et al. (2021) assesses the effects of COVID-19 induced lockdown measures on air quality in both

regional, country, and city scales across 19 countries in the South and Southeast Asian region using satellite-based data. In an assessment and comparison of the effects of lockdown measures on air quality levels between standard business patterns and the current COVID-19 lockdown, the authors use satellite observation-based reanalysis data and satellite-based measurements to monitor the effect of COVID-19 lockdown measures on the levels of NO_2, SO_2, CO, $PM_{2.5}$, and O_3 in the atmosphere. Among the 19 studied cities, the highest reduction of NO_2 during the lockdown period compared to the corresponding period of 2019 were experienced in Dhaka (–40.56%), Kathmandu (–40.99%), Jakarta (–46.87%), and Hanoi (–45.79%). These effects appear to be associated with early declarations of the pandemic as a national disaster, implementation of large-scale social distancing measures, closed restaurants, suspension of international air travel, and measures to restrict mobility and reduce transportation to control human movements.

Similarly, Nakada and Urban (2020) estimated that the partial lockdown in the city of Sao Paulo, Brazil resulted in a 64.8% reduction in carbon monoxide (CO) levels and a 54.3% reduction in NO_2 levels in the air compared to the previous 5 years' monthly average values. Kerimray et al. (2020) assess the impacts of traffic-free conditions in the city of Almaty, Kazakhstan, and they estimate that concentrations of $PM_{2.5}$, NO_2, and CO in the air decreased by 21%, 35%, and 49%, respectively.

Zambrano-Monserrate and Ruano (2020) use a parametric approach to analyse data on NO_2, $PM_{2.5}$, and O_3 concentrations from seven monitoring stations in Quito, Ecuador. The findings show that concentrations of NO_2 from all seven stations are lower in 2020 than in 2018 and 2019. The comparison of concentrations of $PM_{2.5}$ was mixed across monitoring stations, and there was a considerable increase in O_3 in 2020 compared with 2018 and 2019. Similarly, Zalakeviciute et al. (2020) investigated the impact of reduced human activities on urban air quality in Quito and found significant reductions in the concentrations of NO_2 (–68%), SO_2 (–48%), CO (–38%) and $PM_{2.5}$ (–29%).

Mostafa, Gamal, and Wafiq (2021) use satellite imagery and remote sensing technologies to examine the impact of COVID-19 lockdown measures on a range of environmental indicators in Egypt and found that the absorbing aerosol index (AAI) decreased by approximately 30% during the lockdown period of 2020 as compared to the equivalent period in 2019. In addition, concentrations of NO_2 decreased over Cairo by approximately 15%, and in Alexandria by 33%. In addition, the authors find a reduction in environmental noise, solid waste pollution in beaches, and surface and groundwater pollution during the COVID-19 lockdown, but they also find an increase in municipal and medical wastes and less efficient waste recycling.

Dramatic changes in human behaviour in response to the COVID-19 pandemic demonstrate that widespread reductions in a range of pollutants are possible. Air quality is improved in a number of cities, along with a reduction in emissions of greenhouse gases that contribute to global warming. A similar reduction in water pollution and litter is documented in some regions (Mostafa, Gamal, and Wafiq 2021). However, these improvements are likely to be temporary as the virus is eventually contained and economic activity returns to pre-pandemic levels associated with greater mobility and industrial activity. There is much uncertainty regarding the future of commercial real estate, including office buildings, retail shops, and other workplaces, which have largely remained closed during the pandemic as certain segments of society adjust to remote work. Similarly, the increase in municipal and medical waste is likely to be temporary if waste recycling increases in efficiency and vaccinations reduce the need for widespread use of personal protective equipment.

Education impacts

An examination of the literature on second-order education-related effects of the COVID-19 pandemic reveals useful information related to certain social outcomes and variables. These effects include the widespread exacerbation of already existing inequalities surrounding education and general social vulnerability.

Burgess and Sievertsen (2020) suggest that the global lockdown of education institutions during the COVID-19 pandemic will cause major interruptions in students' learning, disruptions in internal assessments, and the cancellations of learning assessments for qualifications (or their replacement by an inferior alternative). They note further that these impacts are likely to be unequally distributed. These interruptions will not likely be a short-term issue, but rather will have long-term consequences in terms of increased inequality of human capital growth for the affected cohorts.

Putra et al. (2020) assess the learning experience of students at home during the school closing period in response to the COVID-19 pandemic in Indonesia. They note significant difficulties and challenges to student learning from home due to inadequate educational opportunities and resources such as a lack of access to the Internet and parents' inability to support their children in the learning process. They suggest the continuation of school closures is likely to increase the inequality of learning outcomes. Similar conclusions have been

documented in research on the impacts to higher education in India (Jena 2020), Nigeria (Jacob, Abigeal, and Lydia 2020), and the Philippines (Toquero 2020), among others.

Research conducted by Human Rights Watch (2020) shows that the closure of schools caused by the pandemic across sub-Saharan Africa exacerbated previously existing inequalities, and that children who were already most at risk of being excluded from a quality education have been most affected. This study found that many children received no education after schools closed across the continent in early 2020, and it highlighted the negative impacts on learning, mental health consequences of social isolation, and disproportionate effects to the education of girls. These impacts reveal implications for inter-generational education inequalities for millions of children.

The long-term social impacts of the COVID-19 pandemic are perhaps the least well understood. The temporary closure of schools and universities, and the associated shift to remote learning, is likely to have negative effects on the education and preparedness to enter the workforce or pursue opportunities for higher education of hundreds of millions of young people (Burgess and Sievertsen 2020; Jacob, Abigeal, and Lydia 2020; Jena 2020). Few studies have used geospatial applications to examine the impacts of the COVID-19 pandemic on education and learning. Given the critical nature of education for human development, there is a need for spatial analysis of school closures, availability of remote learning opportunities, and access to digital technologies over time.

Migration/mobility impacts

Researchers have taken several approaches in examining migration. The literature illustrates the pandemic's effects on migration and population movements. The COVID-19 pandemic has significant implications for migrant workers, remittances, and food security in numerous areas around the world.

Yi et al. (2020) conducts a population-based survey of migrant workers in Singapore to assess dormitory attributes, social ties, physical and mental health status, virus-related variables, and mobility patterns using a grid-based network questionnaire. The study concluded that geospatial networks of migrant workers should be considered in the implementation of lockdown exit strategies while addressing the improvement of living conditions and monitoring systems. Karim, Islam, and Talukder (2020) highlight the impacts of COVID-19 on the 13 million migrant workers in Bangladesh and 30 million dependents. These effects include shrinking remittance flows, depleted savings, and the emergence of socio-economic crisis. The authors emphasize the policy implications of these effects, including tactful efforts required to overcome the effects of COVID-19 on migrant workers.

Truelove et al. (2020) discuss possible effects that COVID-19 transmission among migrants in camps might have later in the pandemic (post-June, the time of the article's publication) on government policies surrounding hospital usage, and access to medical care. However, this discussion of secondary effects is mainly confined to the predictive realm. In this article, Truelove et al. (2020) utilizes geospatial data most rigorously in pursuit of goals surrounding first-order impacts rather than second-order.

Reverse migration is another aspect in examining mobility and migration. Mukhra, Krishan, and Kanchan (2020) examine the issue of migration from urban areas to the countryside, a major secondary impact of COVID-19. The authors describe the effect in India as 'the second largest mass migration in its history after the Partition of India in 1947' (Mukhra, Krishan, and Kanchan 2020, 736). They draw attention to the geographic regions most affected by the pandemic. Nevertheless, a more rigorous discussion of this and other topics related to reverse migration in India (and other places) is in order, a geospatial approach likely being the most effective due to the spatial nature of migration flows.

We align this emerging literature with the C2M2 programme to design methods and approaches to generate data and demonstrate geospatial approaches to inform decision-making and mitigation strategies.

Discussion and conclusion

As the COVID-19 pandemic continues to surge around the world emerging issues of vaccination supply and access (WHO, 2021), increasing problems with trash associated with medical waste and masks (Benson, Bassey, and Palanisami 2021) and long-term economic impacts on women in the workplace (McKinsey & Company 2021). Science has entered an unprecedented phase of delivery in the form of vaccines, modelling of disease spread, and demographic dynamics of vulnerable populations (Nature 2021). The findings of studies cited in the literature review reveal how second-order impacts of the COVID-19 pandemic manifest and provide examples of geospatial approaches.

We observe that each C2M2 project is directly related to the second-order impacts discussed in the literature review. For example, specific C2M2 cities have experienced the impacts of reduced tourism, most notably Kathmandu, Nepal; Nairobi, Kenya; Quito and Santa

Cruz, Ecuador and Ouro Preto, Brazil. Migration of people across South America was occurring before the pandemic due to political instability in Venezuela; the pandemic has served to increase migration across international boundaries. The C2M2 Latin America hub focuses on the impact of changing migration patterns on poverty in Santiago, Chile; Lima, Peru; and Quito, Ecuador. The C2M2 Africa hub focuses on school closures across the three cities (Nairobi, Kenya; Bukavu, DRC; and Pemba, Mozambique). Access to health services is an underlying issue amongst all C2M2 cities; however, Ulaanbaatar, Mongolia faces a particular challenge due to the intersection of poor air quality in informal 'ger' communities and lack of health facilities. Similarly, the informal settlements of Bukavu, Democratic Republic of Congo has limited health services.

The COVID-19 pandemic facilitates important geospatial approaches and applications to address and mitigate its long-term impacts. Our paper provides an overview of an emerging literature on second-order impacts due to COVID-19 with the aim to identify geospatial approaches for the C2M2 programme. Our literature review results highlight that a geospatial approach is limited in the previous COVID-19 second-order impacts papers. Many of these studies focus on regional or national-level data and did not use fine-scale data to understand the second-order impacts at a local level. This finding provides a strong rationale for C2M2 partners to collect and analyse fine-scale geospatial data on the COVID-19's second-order impacts in their cities. The C2M2 project can fill a data gap of these previous studies by demonstrating the utility of local, urban data to analyse COVID-19's second-order impacts.

Each C2M2 project provides an opportunity to generate appropriate-scale data needed to address issues related to economic, environmental health impacts, education, and mobility/migration concerns. The MapGive C2M2 website (Resources tab) is a resource for C2M2 city partners enabling them to learn about research results that pertain to their regions and topics. C2M2 city partners collect, analyse, and map geospatial data valuable to local governments, policy makers, and other decision makers to inform efforts to mitigate the negative second-order impacts of the COVID-19 outbreak, and facilitate activities in support Sustainable Development Goals that have been impeded or reversed as a result of the pandemic.

The pandemic is a transformative event on the world stage where innovative approaches to addressing the second-order impacts are needed. Adopting participatory approaches that include mapping, generation of spatial data by community members and students, and creating an environment for interactive collaboration and modelling are all part of C2M2 projects and activities. Using causal loop diagrams (CLD), C2M2 programme partners illuminate the complexity and connectivity of COVID-19 second-order impacts in their community (Figure 2). CLDs are useful tools to identify variables and linkages to inform data collection and analysis.

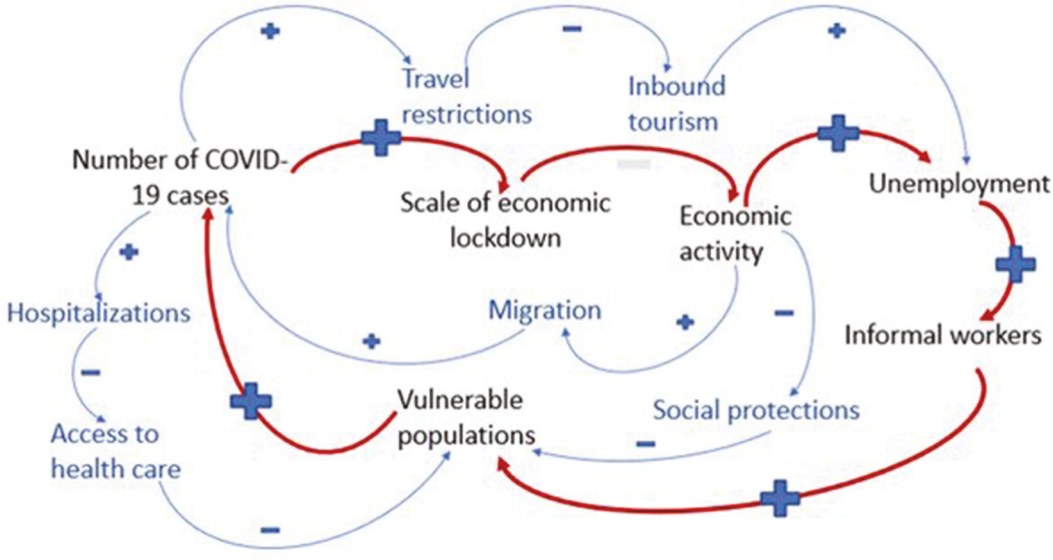

Figure 2. Causal loop diagram. First-order impacts (number of COVID-19 cases) lead to second-order impacts. For example, increasing numbers of cases create more vulnerable populations and fewer social protections for more people. (Graphic provided by R. Richardson, 2020).

Geography is central to the COVID-19 story and the underlying science. Many questions related to the current pandemic are geographic in nature and geospatial applications can help other sciences better understand its roots, its spread, and ultimately its management.

From this initial assessment, the literature reveals 1) the relationship of vulnerable people and the virus to inequitable outcomes; 2) the integration of economic data with geographic information to track supply chains in moving essential items to market; and 3) the unintended outcomes to environmental changes (i.e. air quality). Research on second-order impacts of the pandemic is rapidly emerging and highly dynamic; our database and literature review will expand as new articles are published and identified.

The C2M2 program is an example of the type of projects that can address this crucial data gap, at scale. Relevant local projects using appropriate geospatial tools and technologies ensure the training of the next generation of geospatial practitioners and decision makers who have experienced the pandemic first-hand. Developing policies and strategies to address impacts depend upon an inclusive approach where communities and governments work together transparently. The pandemic demonstrates the impact across different spatial scales from the molecular to the global. It also reveals the need for conversations across disciplines for comprehensive, innovation solutions. Critical to these interdisciplinary examinations is the need for scalable and timely geospatial data. The C2M2 programme facilitates a participatory approach using geospatial tools where government, society and science intersect.

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