Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Remote sensing imagery is considered a useful tool to inform decision-making in a variety of contexts (King, 2003). The information derived from remote sensing imagery has been utilized in contexts like natural disaster response (Pu-tao et al., 2011), informing international conflicts, border disputes and monitoring human rights violations (Avtar et al., 2021), and improving food security through monitoring agricultural activities (Brown, 2016). Spatial epidemiology also makes use of RS imagery in several ways (Beck et al., 2000; Hay, 2000). RS is further widely used by the scientific community in research related to the functioning of the Earth’s various systems.
In 2019 a respiratory disease caused by the Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) led to a pandemic that had a profound impact on global society (Malik, 2020; Zheng, 2020). The infection, named COVID-19, spread to 220 countries and territories, putting severe pressure on public health infrastructure across the world (Hrynick et al., 2021) and had led at the time of writing to over 4.9 million deaths. To control the spread of the virus, governments put a variety of measures in place to restrict international and local movement of people, and economic activities (Alsolami et al., 2021; Sarkodie and Owusu, 2021). Because of this, the pandemic dramatically affected the movement and activities of people as well as the global economy. The scale of the change in anthropogenic activities also led to measurable changes in the environment, for example in air and water quality around the world (Rupani et al., 2020).

Satellite remote sensing data was used widely by government, humanitarian, and private bodies during the pandemic. National...
space agencies and other geospatial organizations like the GEO Group on Earth Observations realized early on the possible value that remote sensing data could supply to help respond to the pandemic, and therefore organized a number of global campaigns and ‘geohackathons’ to engage the geospatial community and work towards solutions to combat the pandemic (GEO, n.d.; Margetta, 2021; Mastracci, 2020). Commercial satellite data providers like Maxar and Planet also held initiatives to make their data openly available to stakeholders (Maxar, n.d.).

In this article, we aim to give an overview of the types of information offered by remote sensing to help address different issues related to the COVID-19 pandemic. We also discuss about the stakeholders that benefited from the data, and the value added by its availability. The reason for this is threefold. Firstly, there is to our knowledge no previous article giving a review of remote sensing during the pandemic. Previous review studies focus more broadly on the use of GIS technology and spatial information during the pandemic, but do not give particular attention to remote sensing data (Franch-Pardo et al., 2020). Secondly, the unique case study offers us an opportunity to ‘take a step back’ and evaluate the extent to which remote sensing imagery contributes value in different spheres. The COVID-19 pandemic is a valuable case study in this regard, since it simultaneously affected society, economy, public health, food security, and the environment. Satellite imagery is already established as a decision-maker’s tool in all these settings and could thus be used to simultaneously inform these different types of issues, and at a global scale. The third motive is to offer a catalogue of the variety of uses and implementations of RS imagery in such types of global disasters, which can serve as a reference for stakeholders during similar future events.

This article draws on scientific literature as well as press articles, brochures, and other materials published on platforms like the web portals of government space agencies or reputable news agencies. The content is presented under four sub-sections; namely (1) the use of RS in real-time decision-making and strategic planning during the pandemic; how RS revealed the (2) environmental changes and (3) social and economic impacts caused by the pandemic. And (4) how RS informed our understanding of the epidemiology of SARS-CoV-2.

2. Methodology

We firstly queried Web of Science, Google Scholar, and Semantic Scholar with different combinations of keywords like ‘Remote Sensing’, ‘COVID-19’, and ‘Satellite Imagery’. We identified sub-topics based on the search results, and then refined search terms to get more specific results for each topic, e.g., ‘Economic impacts’, ‘Satellite’, ‘COVID-19’ in the case of the topic related to the role that remote sensing played in understanding economic impacts of the pandemic.

We also considered certain not peer reviewed sources. Some of the remote sensing applications during the pandemic were not primarily for research reasons and were thus not yet published in academic literature. The work was still however reported for example on the websites of the humanitarian organizations or space agencies involved. One central source in this regard is the Group on Earth Observations (GEO) Community Response to COVID-19 Dashboard (GEO, 2021) which aimed to be a central repository for different COVID-19 related geo-applications.

The sub-topics we identified and number of peer reviewed and not peer-reviewed literature we considered for topics were: (1) supplying operational information to support responses to the pandemic, with 8 peer-reviewed and 7 not peer-reviewed sources, (2) environmental impacts, with 15 peer-reviewed and 0 not peer-reviewed sources, (3) monitoring socio-economic impacts of the pandemic using remote sensing, with 4 peer-reviewed and 2 not peer-reviewed sources, and (4) remote sensing in epidemiological studies, with 13 peer-reviewed and 1 not peer-reviewed source.

Finally, we compiled a table (Table 1) summarising the types of remote sensing methods that are mentioned in this study, with their applications and limitations.

3. Results

3.1. Supplying operational information to support responses to the pandemic

Remote sensing imagery has been used to aid governments and other stakeholders in their campaigns against the COVID-19 pandemic by supplying real-time data of on-the-ground conditions to decision makers. This data has also allowed a variety of activities to continue operation that would otherwise have been inhibited.

3.1.1. Directly related to pandemic

Recent satellite imagery helped governments to rapidly identify areas with a possible high risk of disease transmission. High-resolution images were used to create updated land use maps of urban areas. This information on current land use, together with other demographic, economic and local disease prevalence data was used to identify areas where authorities could focus their epidemic response (e.g., identifying at-risk locations that should receive priority virus testing, etc.) (Kanga et al., 2021). In one application, UAV (unmanned aerial vehicle) based remote sensing data was used to measure the density and crowding of fishermen on fish landing beaches in coastal Ghana during the pandemic (Okyere et al., 2020). The study supplied quantitative data to inform local policy about social-distancing measures for the artisanal fishing industry. On a broader scale, satellite imagery is being used to map areas in low income and violence affected regions that were inadequately mapped before. The Humanitarian OpenStreetMap Team (HOT) allows volunteers to make updated maps of underserved areas by identifying and mapping features from high-resolution publicly available satellite imagery on a web-based platform (HOT, 2020). These efforts enable disaster management teams and local authorities to respond more effectively to the COVID-19 pandemic in areas with inadequate official spatial data.

Satellite imagery aided authorities in the monitoring of the COVID-19 pandemic in regions where disease data was not sufficiently available. The COVID-19 death toll in the Aden governorate, Yemen was estimated using high-resolution satellite imagery of
cemeteries to count freshly buried graves. This data allowed the timing and extent of the pandemic impact in the region to be estimated. The peak burial activity ranged from April to July 2020, with an estimated death toll of 1823 in May (Besson et al., 2020).

The movement and distribution of people in urban and rural areas were altered during the pandemic, due to movement restrictions by regional authorities and changes to economic activities. Authorities monitor these changes to anthropogenic activities to evaluate the implementation of their policies to curb the disease spread and to plan further interventions. Data of nighttime lights showed changes in the activities and distribution of people in urban centres in various parts of the world (Deep and Gupta, 2021; GMS, 2020; Roberts, 2021). This included reduced activity in commercial areas, and in some cases increased activity near medical centres (Duncombe, 2020).

Very high-resolution UAV-based remote sensing has been proposed as a tool to monitor crowds and identify possible COVID-19 cases (UNICEF Supply Division, n.d.). In this application, thermal cameras are used to remotely monitor temperature anomalies in crowds and identify possible infected individuals (Pandey et al., 2021). However, this has been met with considerable opposition by human rights groups and caused controversy due to concerns about privacy issues (Guenot, 2021).

3.1.2. Actionable information to support other activities affected by the pandemic

During the pandemic, there were large-scale supply chain disruptions that also affected the shipping industry. This led to congestion outside ports. In response, high-resolution optical imagery was used to monitor activities in ports around the world. The information helped shipping companies better coordinate vessels and so reduce delays (Dharmani, 2020). Satellite imagery also supplemented data for research and other projects when field surveys were inhibited by travel restrictions. The Svalbard Integrated Arctic Earth Observing System (SIOs) research network hosted a campaign to help their researchers identify suitable remote sensing data alternatives to substitute cancelled field surveys during the period of global travel restrictions (Jawak et al., 2021). Government and private entities also used satellite imagery to substitute fieldwork that couldn’t happen due to the pandemic (Maroney and Robillard, 2020; Politzer, 2020). In Chile, Sentinel-2 and Sentinel-3 imagery (see Table 1) substituted in-situ surveys for harmful algal blooms (HAB) in the ocean off the coast (Rodriguez-Benito et al., 2020). Chile’s large aquaculture industry often suffers losses from phytoplankton blooms, and therefore the government has an extensive water monitoring network in place to act as an early warning system. During the strict lockdown period in Chile, the HAB monitoring activities were also strained, yet this period coincided with a large bloom that led to aquaculture losses. At this time data from the Ocean and Land Colour Instrument (OCLI) on-board Sentinel 3 was used to capture the algal bloom and provide operational monitoring (Rodriguez-Benito et al., 2020). Remote sensing data thus aided government, private companies, humanitarian, and research organizations in their various activities during the pandemic. This point is summarised in Fig. 1.

3.2. Monitoring environmental impacts of the pandemic using remote sensing

During the pandemic industries, transport networks and people’s activity suddenly halted. This led to a reduction in the various types of pollution and environmental impacts that are associated with anthropogenic activities. Remote sensing imagery captured the extent of these changes in the atmosphere, biosphere, and hydrosphere during the pandemic. This measurable example of how changes to people’s activities directly improved environmental conditions may be a stimulus for improved environmental policy. This is mentioned in Fig. 1.

3.2.1. Air pollution

After the outbreak of COVID-19 and resulting lockdowns, there was a decline in air pollutants from major cities of East Asia, Europe, and the USA (Venter et al., 2020; Ghahremanloo et al., 2021). RS data helped to monitor the changes in concentration of various air pollutants, in conjunction with ground-based air quality sensors. The main satellite sources used were the TROPOMI
instrument on the Sentinel-5P satellite (see Table 1), which supplies Nitrogen Oxides (NOx) and Ozone concentrations data since 2018 (Venter et al., 2020), and the hyperspectral OMI sensor aboard the Aura satellite (Table 1), which measures ozone, SO2, aerosols, and other air pollutants (Levett et al., 2018; Nichol et al., 2020). Data for particulate matter and aerosol depth was also sourced from the MCD19A2v006 data product, derived from MODIS imagery (Venter et al., 2020). Studies also directly used meteorological data to account for meteorological factors that could influence pollution levels, apart from the changes to anthropogenic activities. The limitation of satellite data in this application was however that air pollutants concentration is measured for the entire air column and did not directly reflect air quality at ground level. The measurements are also affected by aerosols and particulate matter traveling long distances from its source. Therefore, studies combined satellite observations, giving a global spatial coverage, with measurements from in-situ air quality sensors, that give accurate ground level pollution data.

Outcomes from various studies demonstrated that the concentration of PM2.5, NO2, HCHO, SO2, AOD, and CO declined significantly compared to the baseline period of February 2019. A large reduction in pollutants occurred in Wuhan, with a decrease of almost 83%, 11%, 71%, and 4% in the column densities of NO2, HCHO, SO2, and CO, respectively, and a decrease of about 62% in the AOD (Ghahremanloo et al., 2021). Some areas however experienced increased smog, and higher concentrations of specific pollutants due to changes in urban airflow and atmospheric chemistry. Studying these phenomena might lead to a better understanding of urban smog formation (Le et al., 2020).

3.2.2. Measuring the COVID-19 pandemic’s impact on the marine and freshwater environments

After the COVID-19 pandemic outbreak, governments put in place measures to inhibit movement and activities of people. These lockdown measures had knock-on effects on water quality, caused by changed industrial, marine, and agricultural activities. (Vijay Prakash et al., 2021).

Time-series satellite imagery revealed the effect of anthropogenic activities on river and lake pollution. Optical Landsat 8 OLI data (Table 1) showed decreased turbidity levels for a section of the Sabarmati River in the Ahmedabad region and the entire length of Ganges River in India (Aman et al., 2020; Muduli et al., 2021). Similarly, time-series of Landsat 8 OLI data and China’s Gaofen-1 satellite data showed sharply decreased total suspended solids in the Min River in China in January–February 2020, coinciding with strict lockdowns (Xu et al., 2021). A study in Morocco used Sentinel-3 data to investigate the Water Surface Temperature (WST) in Tangier coastal environment before and during the pandemic in Morocco. During the lockdowns river temperature decreased, probably in response to reduced waste discharge from upstream industries (Cherif et al., 2020). Prohibiting tourist activities also led to improved water quality. A study in the Venice Lagoon (Italy) found a 50% reduction in total suspended matter (TSM) after lockdown through Very-High Resolution (VHR) PlanetScope Imagery (Table 1) (Mousazadeh et al., 2021; Niroumand-Jadidi et al., 2020). Since the reduction of tourists, water quality along beaches in Acapulco (Mexico), Barcelona (Spain), and Salinas (Ecuador) improved noticeably (Ormaza-Gonzalez et al., 2021; Zambrano-Monserrate et al., 2020). Wagh found a significant reduction in lake water pollution due to lockdown in Lake Hussain Sagar (India) by using two techniques: spectral reflectance and chromaticity analysis (Wagh et al., 2021). The study also observed that pollution concentration levels in the lake were more uniformly distributed during the lockdown, as compared to before lockdown, after the lockdown was lifted (2020) or previous years (2015–2019). This suggests that the lake pollutant concentration was uniformly distributed on the lake surface due to low effluent influx during the lockdown (Wagh et al., 2021).

Changes to people’s activities affected nutrient loading and algal growth in marine and freshwater environments during lockdowns. Chlorophyll-a (Chl-a) in lakes in Wuhan, China, was monitored using Landsat-8 and Sentinel-2 sensors (Table 1). The lakes showed elevated concentrations of Chl-a, possibly because of the decrease in recreational activities during COVID-19-induced lockdown (Avtar et al., 2020). Marine algal blooms were also detected off the coast of Chile (Rodríguez-Benito et al., 2020) and in the Arabian Gulf (Polikarpov et al., 2021) during the time of lockdowns. In the case of the Arabian gulf, the blooms were linked to increased nutrient loading in Kuwait bay.

Above-mentioned studies demonstrated that short-term changes in anthropogenic activities have a measurable effect on water quality. In this way remote sensing can motivate improved environmental policy that will benefit water quality in the long term (Fig. 1). The studies also show how higher resolution sensors can capture the water quality variations over short time periods, and in smaller water bodies, including rivers (Mousazadeh et al., 2021; Niroumand-Jadidi et al., 2020; Wagh et al., 2021).

3.3. Monitoring socio-economic impacts of the pandemic using remote sensing

In this section, we will discuss how satellite data was used to monitor changes in economic activities and human society during the COVID-19 pandemic. Since the pandemic spread globally, the economies of almost all countries were affected (Maital and Barzani, 2020). Changes to economic activities and new policies governing the movement and activities of people also had knock-on social impacts, like changed distribution of people between urban and rural areas, loss of people’s livelihoods, and changes to food supply and employment (Minetto et al., 2021). mentions that “Economic activities impact social behaviours, which leave signatures in satellite images that can be automatically detected and classified”, but how can we use the information from satellites to analyse economics effectively?

High-resolution imagery such as WorldView-3 can directly identify objects on the ground that indicate economic activities (Sobue et al., 2020). For example, by detecting cars researchers can get traffic information (Chen et al., 2021) and estimate activity at shopping centres. Objects like bulldozers, excavators, trucks, and tents give information about construction activities (Minetto et al., 2021). Drops in the number of flying aircraft over Europe could be detected from Sentinel 2 imagery (Segundo et al., 2021). These data can benefit studies on the spatial variation and timing of economic impacts caused by the pandemic. City and national level policymakers could also use this type of data as one source, among others, to evaluate how changes to government policy affected activities
on the ground. Additionally, authorities can monitor how changes to economic activities vary spatially (i.e., between different land-use types, across different administrative units, etc.). This information can help authorities verify that policies are being implemented correctly and might inform future policy changes. Finally, remotely observing disruptions to livelihoods in specific areas can serve authorities as an early warning system against local poverty, possible food shortages, and accompanying social unrest. A case study in India used satellite imagery to estimate how many fishermen’s livelihoods were affected by the different phases of local lockdowns (Avtar et al., 2021). During the strict lockdowns in India, the number of boats in some Indian harbours increased dramatically. Fishermen were not allowed to work, so many returned their boats to the harbour. The authors used VHR imagery, together with a Support Vector Machine (SVM) classifier to detect the area covered by boats in the harbour.

Economic and social indicators can also be sourced from a variety of conventional sources like economic surveys. Remote sensing does not replace these sources, because remote sensing only offers proxies of economic activities, which can be compared over time or between locations. Still, satellite imagery offers the advantage of being able to measure a variety of indicators from the same data source, bypassing the complexity of integrating information from heterogeneous sources that have differing formats, spatial and temporal resolutions, and are compiled and stored by different stakeholders in different locations. Satellite imagery can also be used to measure indicators in new locations quickly, and it is comparably easy to scale investigations up to a national or even global scale while still using the same data source and methodology (Minetto et al., 2021).

3.4. Remote sensing in epidemiological studies

Epidemiology involves the study of the spread, distribution, and causes of diseases and other health conditions (Porta et al., 2014). Remote sensing is recognized as a tool to aid epidemiological studies by providing spatial information about determinants of diseases, like disease vector habitats (in the case of vector-borne diseases), or meteorological conditions associated with the spread of the disease (Polgreen and Polgreen, 2018). In this section, we introduce how satellite data was used in epidemiological studies of COVID-19. In this application satellite data was particularly useful to study the links between meteorological conditions and disease spread.

3.4.1. Meteorological variables and propagation of COVID-19

There has been considerable speculation on which meteorological variables affect the spread of SARS-CoV-2 (Gupta et al., 2020; Sajadi et al., 2020). In response, studies used data products that incorporated ground-based, radar, and weather satellite data, like NLDAS (Ma et al., 2021) or ERA5 (Runkle et al., 2020) to relate spatial variation in disease transmission rates with local air temperatures, humidity, and air pressure. Satellite data allowed researchers to easily compare meteorological variables and disease variation in different areas, at the country (Correa-Araneda et al., 2021; Qi et al., 2020) and global level (Zhang et al., 2021). Being able to simultaneously consider widely varying areas (varying in demography, public health response, etc.) helped to control for other confounding variables that could influence results found just at the local scale (Briz-Redón and Serrano-Aroca, 2020; Zhang et al., 2021). In their study of 1236 separate spatial regions across 124 countries, Zhang et al. (2021) fed local temperature and humidity parameters from the ERA5 climate reanalysis dataset into a multivariate regression model that also accounted for social and economic variables that vary across regions. The study found that low temperature and humidity both correlated to increased disease spread and it also quantified how the strength of the interaction varied across wealthy and poor regions. Therefore, by supplying weather data at the global scale, remote sensing helped to produce more robust epidemiological results that are arguably applicable to more areas. Studies correlating disease spread with other geographic factors also relied on data sourced from remote sensing, e.g., the Shuttle Radar Topography mission as a source of topography data, and long-term weather satellite data (Table 1) to inform climate variables (A. Gupta et al., 2020).

3.4.2. Nitrogen dioxide (NO$_2$) and propagation of COVID-19

Nitrogen dioxide mainly affects the respiratory system, by increasing the risk for respiratory tract infections. The interference of nitrogen dioxide on the expression of the ACE2 enzyme - which is the cell receptor for the SARS-CoV-2 virus - might also be one aspect of COVID-19 spread (Alifano et al., 2020). Studies using remote sensing techniques stated that exposure to NO$_2$ may be one of the most important environmental determinants for the spread and fatality caused by the COVID-19 disease (Copat et al., 2020). Ogen (2020) collated the number of fatal cases from 66 administrative regions in Italy, Spain, France, and Germany and correlated mortality with tropospheric NO$_2$ concentrations measured by the Sentinel-5P satellite. The major tropospheric NO$_2$ hotspot identified was in Northern Italy. Results showed that out of the 4443 fatality cases by March 19, 2020, 3487 (78%) were in five regions located in north Italy and central Spain, concluding that long-term exposure to NO$_2$ may be a potential contributor to mortality caused by SARS-CoV-2. Another study in Northern Italy compared NO$_2$ levels with SARS-CoV-2 prevalence rate at different time points after the lockdown, namely March 8, 22, and April 5. They found a positive association between levels of NO$_2$ levels and subsequent prevalence of SARS-CoV-2 in Northern Italy, though this occurred only at high levels of NO$_2$ (up to about 130 $\mu$mol/m$^3$).

3.5. Overview of discussed remote sensing methods

As a reference to the reader, we have compiled a table (Table 1) that describes the different types of remote sensing discussed in this article together with their main applications and limitations. This table is not exhaustive, as we focus on passive remote sensing techniques, and give reference primarily to the satellites and sensors introduced in this article. For a more complete discussion on remote sensing techniques and applications, see (Kuenzer et al., 2014; Zhao et al., 2022).

4. Discussion & conclusion

In this article, we reviewed how satellite and to a lesser extent UAV imagery proved useful in several applications during the
This is in part because many methods described in the article are still novel, and the relationships are not established between indicators inferred from satellites and the real-world phenomena that they represent. For example, the change in cars parked near shopping centres indicates changes in economic activity, but the exact quantitative relationship is still to be established. For a number of applications, remote sensing imagery can only approximate changing conditions, but cannot directly measure variables of interest (e.g., agricultural outputs, job losses, or real changes to economic growth.) As such, remote sensing should be considered as a supplementary data source that can be used synergistically with other established methods of measuring various variables of interest (e.g., agricultural outputs, job losses, or real changes to economic growth.)

Finally, however, we need to point out that remote sensing is not a ‘silver bullet’ that promises to fill most knowledge gaps (Herbreteau et al., 2007). This is in part because many methods described in the article are still novel, and the relationships are not established between indicators inferred from satellites and the real-world phenomena that they represent. For example, the change in cars parked near shopping centres indicates changes in economic activity, but the exact quantitative relationship is still to be established. For a number of applications, remote sensing imagery can only approximate changing conditions, but cannot directly measure variables of interest (e.g., agricultural outputs, job losses, or real changes to economic growth.) As such, remote sensing should be considered as a supplementary data source that can be used synergistically with other established methods of measuring various targeted indicators. Overall, we think that remote sensing will however remain a very useful tool in its various applications, especially in disaster situations, as we saw during the COVID-19 pandemic. The value of this technology should also increase over time, as the quality and quantity of data improves, and methods of analysing and extracting useful information mature further. To promote the utilization of remote sensing data, we should continue to develop and promote platforms where useful information can be made readily available to non-expert stakeholders, for example through web or mobile applications.

### Ethical statement

Ethics approval was not required for this research.

### Declaration of competing interest

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

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