Remote Sensing Applications: Society and Environment 27 (2022) 100789

Contents lists available at ScienceDirect

Remote Sensing Applications: Society and Environment

journal homepage: www.elsevier.com/locate/rsase

The role of remote sensing during a global disaster: COVID-19 pandemic as case study

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ARTICLE INFO

Keywords:
COVID-19
Remote sensing
Satellite imagery
Decision-making
Pollution
Epidemiology
Economy
Review

ABSTRACT

Remotely sensed imagery is used as a tool to aid decision makers and scientists in a variety of fields. A recent world event in which satellite imagery was extensively relied on by a variety of stakeholders was the COVID-19 pandemic. In this article we aim to give an overview of the types of information offered through remote sensing (RS) to help address different issues related to the pandemic. We also discuss about the stakeholders that benefited from the data, and the value added by its availability. 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, the pathogen responsible for the pandemic. High resolution optical imagery offered updated on-the-ground data for e.g., humanitarian aid organizations, and informed operational decision making of shipping companies. Change in the intensity of air and water pollution after reduced anthropogenic activities around the world were captured by remote sensing – supplying concrete evidence that can help inform improved environmental policy. Several economic indicators were measured from satellite imagery, showing the spatiotemporal component of economic impacts caused by the global pandemic. Finally, satellite based meteorological data supported epidemiological studies of environmental disease determinants. The varied use of remote sensing during the COVID-19 pandemic affirms the value of this technology to society, especially in times of large-scale disasters.

1. Introduction

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 (Fu-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

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https://doi.org/10.1016/j.rsase.2022.100789
Received 25 October 2021; Received in revised form 7 May 2022; Accepted 8 June 2022
Available online 18 June 2022

Table 1
Description of the types of satellite remote sensing introduced in this article. Specific sensor names are given, followed by the satellite platform on which it is carried in brackets.

Type of remote sensing	Sensors & platforms	Application	Limitation	
Very High Resolution (VHR) Optical Imagery	Worldview constellation, PlanetScope constellation	Data products are optical images with red, green, blue, and occasionally near-infrared spectral bands, at a ground resolution below 1 m per pixel (as low as 30 cm). Used for precise mapping of ground features and monitoring ground activities over time, as satellites often also have quick revisit times to the same location.	The low number of spectral bands captured reduce the range of science applications. Data from this type of RS is often provided as commercial products, which increases the barrier to use.	Sagan et al., 2021
High resolution Optical Imagery	OLI (Landsat 8), MSI (Sentinel 2), WVI (GaoFen-1)	Multispectral sensors capture images in between 4 and 10 spectral bands in the visible and infrared parts of the electromagnetic spectrum. Data usually have a ground resolution of between 10 m and 30 m per pixel. This data is used for various applications in urban studies, agriculture, and environment, including mapping land-use, and its changes over time. These datasets are often available to the public freely, and available for multiple years, which has led to widespread adoption by the scientific community.	Slow revisit times to the same location (order of one or two weeks). Images are often obstructed by clouds, which together with slow revisit times cause extended periods without no data. The spatial resolution is insufficient for applications that require distinguishing individual objects like houses or cars.	Xu et al., 2021; E. D. Chaves et al., 2020
Moderate Resolution Spectrometers & Radiometers	MODIS (Terrra & Aqua), OLCI (Sentinel 3), VIIRS (Suomi-NPP)	Data characterised by narrow spectral bands in the UV, visible and infrared spectrum, with more bands captured than in multispectral imagery (e.g., 36 bands for MODIS, 21 bands for OLCI). Data captured by these sensors generally have a ground resolution of between 250 m and 1 km per pixel, and is thus mainly suitable for studies over large spatial scales. The high spectral resolution allows the data to be used for a range of science applications, including studies on the atmosphere, ocean and land colour and surface temperature.	The lower spatial resolution is insufficient for certain applications.	Milne and Cohen, 1999; Hillger et al., 2014
Coarse resolution Spectrometers	TROPOMI (Sentinel 5P), OMI (Aura)	Spectrometers allow for the capture of narrow spectral bands between the UV and IR parts of the spectrum. Data is captured daily, but at low ground spatial resolution (7 km per pixel, or lower) The high spectral resolution allows for distinguishing gas types and aerosols in the atmosphere. This imagery is thus used to study the atmosphere, including ozone, air-quality, and atmospheric chemistry.	Due to the coarse spatial resolution, the data is suitable primarily for atmospheric studies, and localised air-quality and sources of pollution are difficult to measure.	Wang et al., 2020
Weather Satellites	GOES, Meteosat, Fengyun	These satellites capture wind, cloud, temperature, and other atmospheric variables, to supply data for weather monitoring. Geostationary weather satellites capture data over specific regions at high temporal frequency (e.g., every 15 min). The ground spatial resolution for weather satellite data is usually lower than 1 km per pixel.	Weather satellites are primarily limited to weather monitoring applications. The spatial resolution, and band-composition are not well suited for studies such as land cover mapping.	Perez et al., 2013

(Dominguez-Barroso et al., 2006; Greenwald et al., 1999), and research related to the global environment (Jan de Leeuw et al., 2010).

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

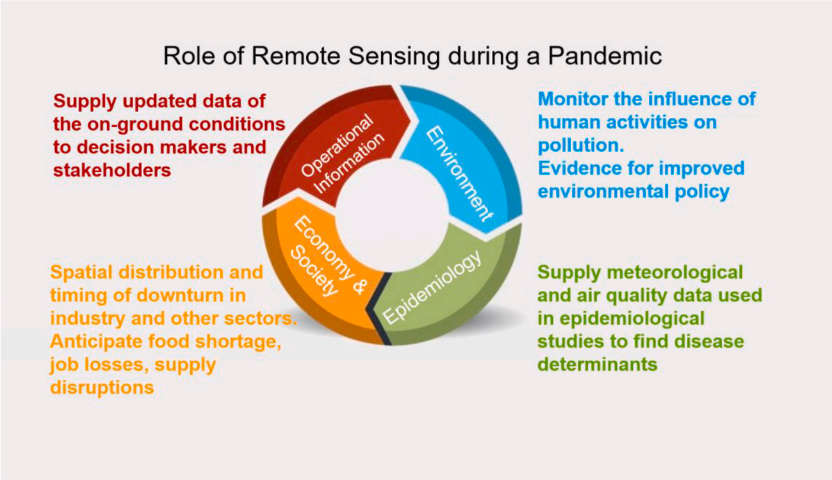

Fig. 1. Summary of the four areas in which remote sensing contributed value during the COVID-19 pandemic.

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 (Rodríguez-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 (Rodríguez-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, SO_2, aerosols, and other air pollutants (Levelt 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 atmospheric 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, NO_2, HCHO, SO_2, 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 NO_2, HCHO, SO_2, 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-Gonzaìlez 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 giving 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 μmol/m^2).

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

Table 2
Different applications of remote sensing during the COVID-19 pandemic. This list is not exhaustive but summarises the findings of this review.

Application	Data source	Reference
Updated land use maps for disease response planning.	VHR imagery	HOT, 2021; Kanga et al., 2021
Monitor changes to activity and distribution of people.	Night-time lights data (VIIRS)	Deep and Gupta, 2021; Duncombe, 2020; GMS, 2020; Roberts, 2021
Estimate mortality in underreported regions.	VHR imagery	Besson et al., 2020
Identify possible infection cases in crowds.	Drone based thermal imagery	Guenot, 2021; Pandey et al., 2021; UNICEF Supply Division, n.d.
Monitor cargo shipping congestion around ports.	VHR imagery	Dharmani, 2020
Alternative data source to substitute postponed field excursion.	Various	Jawak et al., 2021; Maroney and Robillard, 2020; Politzer, 2020
Measure reduced air pollution emissions and changes to air quality during lockdowns.	OMI, TROPOMI, MODIS data products	Ghahremanloo et al., 2021; He et al., 2021; Le et al., 2020; Venter et al., 2020; Roman-Gonzalez et al., 2020
Measure changes in marine and freshwater quality during lockdowns.	OLCI (Sentinel 3), PlanetScope, Sentinel 2 MSI, Landsat 8 OLI	Aman et al., 2020; Avtar et al., 2020; Cherif et al., 2020; Mousazadeh et al., 2021; Muduli et al., 2021; Okuku et al., 2021; Wagh et al., 2021
Automatically Identify objects on the ground that indicate economic activity.	VHR imagery (Planet, xView)	Chen et al., 2021; Minetto et al., 2021
Measure change in flying aircraft activity	Sentinel 2 MSI	Segundo et al., 2021
Observe reduction in tourism activity around African Protected Areas	VIIRS (VNP46A1)	Anand & Kim, 2021
Measure Crop status to predict impacts on food security	MODIS	Balwinder-Singh et al., 2020
Estimate economic losses in the fishery sector.	PlanetScope	Avtar et al., 2021
Supply meteorological data for epidemiological studies of environmental disease determinants	Weather satellites	Correa-Araneda et al., 2021; S. Gupta et al., 2020; Qi et al., 2020; Zhang et al., 2021
Supply air quality data for environmental disease determinants studies	OMI, TROPOMI	Copat et al., 2020; Filippini et al., 2020; Ogen, 2020

COVID-19 pandemic between 2019 and 2021 (summary given in Table 2). Drawing from the sections that precede, we would like to make several remarks. Firstly, we observed that remote sensing data were valuable to a broad range of stakeholders, including decision-makers at different levels of government, health authorities, humanitarian organizations and disaster response units, commercial enterprises, scientists working in climate, environment, and other fields, and epidemiologists studying the disease's spread (Table 2). And together with this, the data was available and useful to stakeholders across the world, in different contexts. Secondly, during the pandemic, the global geospatial community used a wide variety of sensor types and satellite platforms from different government and private providers to inform their various applications (Table 1). These include optical imagery with different spatial and temporal resolutions, nighttime lights sensors like VIIRS (Elvidge et al., 2017), and platforms measuring air quality like Sentinel 5P (Ogen, 2020).

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.

Acknowledgment

We would like to thank Hokkaido University, Japan, and L-station tenure-track grant for providing research facilities. The authors would like to thank anonymous reviewers for their comments and suggestions. This work was partially supported by Kurata Hitachi grant and Kakenhi grant number 21K05664. Three of the authors would like to acknowledge the financial support from MEXT-

Monbukagakusho, Japan scholarship.

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