There is more to satellite imagery than meets the eye

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From the humble first mission of Landsat-1 in 1972 and the Terra/Aqua pair of satellites launched by the American National Aeronautics and Space Administration (NASA) in 1999 and 2004, respectively, the number of Earth-observing satellites now exceeds a thousand (https://www.pixalytics.com/satellites-in-2022), each carrying a variety of sensors. In step with the progress of satellite technology, although along a completely separate trail, geographical information systems (GIS) constitute a highly useful way to store, organize and visualize spatial and temporal data. Its roots reach back to John Snow (1852), who famously brought a cholera epidemic in the Soho District of London to an end by recommending the closure of a water pump after noting its location in relation to the spatial pattern of case residences. Interestingly, the spatial connection to disease was already discussed in Antiquity (Hippocrates, 400 BC) and the German cartographer Heinrich Berghaus book *Atlas of Diseases* (1837) also deserves a mention. This landmark in the history of medical cartography introduced a synthesis of medical mapping based on the role of isothermal lines, winds and climatic zones, which predates today's focus on the role of the environment for vector-borne diseases. Nonetheless, Snow's results remained inexplicable until Robert Koch conclusively established that infectious diseases are caused by bacteria (Blevins and Bronze, 2010), with viruses entering the medical vocabulary not long afterwards (Beijerinck, 1898).

In spite of the progress made, it would be more than a century until epidemiological mapping became an established discipline. After Roger Tomlinson (1974) first used the term GIS in his doctoral thesis on methodology of land inventory in Canada, the Environmental Systems Research Institute (ESRI) (https://www.esri.com/) developed his approach further when working on a land project in California, USA. However, while originally presenting the geographical and geological data on transparent grid overlays, ESRI switched to a computerized version based on vector graphics and raster-format. Combined with a database of the collected spatial data, this approach led to the release of the first commercial GIS application ARC/INFO in 1982.

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Remotely sensed data

When Tom Koch (2011) extended Berghaus (1837) ideas in his excellent chronicle of the history of disease and cartography, Earth-observing satellites were already providing the epidemiologist with unparalleled imagery and measurements of the biosphere. This approach to defining vector habitats presents not only high-resolution, but also hyper-spectral data. Thus, in less than 200 years after the pioneering ideas of Snow and Berghaus, satellite-borne instruments are providing epidemiologists with more essential information that can easily be handled. For example, the moderate resolution imaging spectroradiometer (MODIS) sensor onboard the Terra and Aqua satellites collects continuous 36-band data from land, sea and the lower atmosphere, at spatial resolutions of 250 m (bands 1-2), 500 m (bands 3-7) and 1000 m (bands 8-36). Then again, the remotely sensed products can be integrated directly into epidemiological equations that significantly enhance our understanding of habitats and life cycles of vectors and also those of the parasites they harbour.

Most Earth-observing satellites achieve global coverage due to their near-polar orbits but resolution and revisit times differ, so the outcome of data collection may be improved by combining the records from one instrument with another. Thus, MODIS information may be complemented with data from the dual thermal infrared sensor (TIRS) and the operational land imager (OLI) onboard Landsat-8 and Landsat-9, which have higher resolutions than MODIS in most bands (https://landsat.gsfc.nasa.gov/). However, Landsat has a 16-day revisit cycle, while MODIS views the entire Earth's surface twice daily since both Terra and Aqua are equipped with this instrument and these two satellites orbit Earth in opposite directions.

Sensors onboard the weather satellites operated by the U.S. National Oceanic and Atmospheric Administration (NOAA) can also deliver data of biological interest. The multi-channel radiometer onboard these satellites cover a large section of the electromagnetic spectrum and are capable of recording visible light along with atmospheric cloud temperature, moisture-profiles and ozone distribution. However, to give a fixed image these satellites must match Earth's rotation, which demands an altitude of 35,786 km, high enough for the view from each satellite to cover half the planet. Although the imagery cannot be detailed at that level, a major advantage is that the revisit problem of the near-polar orbits disappears thanks to the continuous view of the same area.

Ecological niche modelling

The view of nature as a set of contiguous niches with diverse ecology was first outlined by Pavlovskii (1945) and later developed by Nix (1986), who produced a habitat model of suitable niches for species under past, present and future conditions. Current research in this area is supported by sources such as the WorldClim databases (Hijmans *et al*., 2005; Fick and Hijmans, 2017) based on a 30-year period at 1-km^2 spatial resolution of variables derived from remotely sensed information of temperature and rainfall interpolated with data from terrestrial weather stations. The success of this approach led Brown *et al*. (2018) to create PaleoClim, a database of similar climate data at a resolution of about 5 km^2 covering the Pleistocene and Holocene epochs. Excavations have revealed human and animal parasitic infections dating as far back as 40,000 years ago (Banks, 2017; Khodkar *et al*., 2018).

The information gained by Earth-observing satellites is of the utmost importance to epidemiologists studying vector-dependent diseases, as the collected data for environmental niches specify which vectors can survive and breed there. Building on the previous ideas about contagious niches, the ongoing climate change have promoted the development of ecological niche models (ENMs) to enable operational vector control by effectively elucidating the ambient eco-epidemiologic risk factors (Feng *et al*., 2019). ENMs can be developed using MaxEnt software (https://biodiversityinformatics.amnh.org/open_source/maxent/) based on an algorithm for maximum entropy specifying a highly reliable spatial and temporal characterisation of a study area.

The new satellite sensors

In the latest decade, a system not only characterized by coverage and resolution but also by the specificity of its measurements has been developed. This new generation includes the soil moisture active passive (SMAP), a dedicated satellite-borne instrument for biological research that combines L-band radar and a radiometer to directly measure the volumetric soil moisture in the top 5 cm of surface soil. SMAP was launched in 2015 by NASA and the data can be obtained from NASA's EarthData site (https://earthdata.nasa.gov/). In areas surrounding the peridomicile of rural and semirural households in the developing countries, the topsoil has a rich organic content corresponding to known microhabitats of microorganisms that can vary from viruses and bacteria to single-cell and multicellular parasites. There is a clear need for innovative and alternative surveillance and response systems with respect to endemic infections, and ENM speciation may enable more effective elucidation of eco-epidemiologic risk factors that could lead to better control measures. One of the articles in this issue of *Geospatial Health* outlines the advantages offered by SMAP data (Rodgers *et al*., 2022). It is highly possible that *direct* Earth-observing satellite measurement of soil moisture by SMAP can be used *in lieu* of models calculated from classical thermal and precipitation climate station data for the assessment of vector risk.

Various specific instruments have been appended to the International Space Station (ISS), operated by a partnership of five national space agencies since its launch in November 1998. Currently, ISS supports novel NASA operational programs of potential public health importance to better define vector-borne diseases in the hypothetical world of ecological niches as envisioned by Nix (1986) more than 25 years ago. Two new sensors launched in 2018 are of particular interest for biological research:

- The *ECOsystem Space-borne Thermal Radiometer Experiment on Space Station* (ECOSTRESS) is monitoring the temperature of planted agriculture from space and capable of indicating when insufficient water makes leaf stomata close and stop the cooling effects of evapotranspiration when wilt due to temperature increase approaches. These data track how water stress affects the carbon cycle in vegetation, thereby producing the Evaporative Stress Index, a critical drought indicator. Indeed, this instrument can specify information for highly limited areas, such as the household level (Malone *et al*., 2019).
- The *Global Ecosystem Dynamics Investigation* (GEDI) instrument has the highest optical resolution of any *LIght Detection And Ranging* (LIDAR) sensor launched into orbit so far. GEDI measures Earth's vegetation in both high-resolution and in three dimensions (3-D) providing unprecedented sensitive, global views of both topographic and biological changes. Its three lasers provide data on surface structures that are valuable for weather forecasting, forest management and glacier snowpack monitoring. In addition, they generate more accurate digital elevation models than been possible before, which is essential for relating hydrology to topography in ENMs. Since GEDI's launch to the ISS in 2018, useful 3-D views of global biomass have been produced, *e.g*., capturing changes in forest canopy due to vegetation disturbances (Francini *et al.*, 2022).

This brief overview focuses on the epidemiological utility of the most used satellite instruments and gives a glimpse of a future that has already started. For those particularly interested in high-resolution imagery there is also a growing private sector that has launched satellites with instruments capable of delivering images with ultra-high resolution (Bergquist and Manda, 2019). Since the USA had a head start in 'orbital' area, most of the sensors discussed here are American, but there are also many other satellites, such as those from the European Space Agency (ESA) as well as national ones, *e.g*., Indian and Japanese satellites that also support research. The data available today do not only support research but assist also policy makers in making sound decisions concerning environmental protection and disease control.

Importantly, the field of Earth-observing satellites is less a competitive race but rather a reflection of close international collaboration. An additional advantage is that a majority of satellite-generated data and imagery can be downloaded free of charge. The future of high-resolution imagery and ENM analysis is giving us the means to base research on combinations of cutting-edge instruments. Interestingly, data from the latest instruments together point at drought stress as the perhaps most important limiting factor in biological cycles through its impact on current vegetation growth.

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