Environmental impacts of increasing numbers of artificial space objects

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For much of their existence, the environmental benefits of artificial satellites, particularly through provision of remotely sensed data, seem likely to have greatly exceeded their environmental costs. With dramatic current and projected growth in the number of Earth-observation and other satellites in low Earth orbit, this trade-off now needs to be considered more carefully. Here we highlight the range of environmental impacts of satellite technology, taking a life-cycle approach to evaluate impacts from manufacture, through launch, to burn-up during de-orbiting. These include the use of renewable and nonrenewable resources (including those associated with the transmission, long-term storage, and distribution of data), atmospheric consequences of rocket launches and satellite de-orbiting, and impacts of a changing nighttime sky on humans and other organisms. Initial estimations of the scale of some impacts are sufficient to underscore the need for more detailed investigations and to identify potential means by which impacts can be reduced and mitigated.

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Human activities in space are growing rapidly. Since the start of the space age in 1957, with launch of the first satellite into orbit (Sputnik), there have been ~6370 rocket launches and ~15,070 satellites placed into Earth orbit, of which ~9790 remain in space and ~7200 are still functioning (Figure 1; WebFigure 1) (https://sdup.esoc.esa.int/discosweb/statistics). While there is debate about the likely size of future growth, predictions suggest that an additional 20,000 launches will occur in this decade alone (Miraux 2021), with between 60,000 and 100,000 satellites in low Earth orbit (normally <2000 km altitude) in the decades (and potentially soon) thereafter (Venkatesan *et al*. 2020; Miraux 2021; Walker and Benvenuti 2022). Much of this expansion is driven by ongoing, planned, and predicted creation of privately owned satellite mega-constellations. For the most part, these provide internet services, and although they can service off-grid communities, they have been marketed as replacements to cable-based internet for global communities (eg the "Starlink", "SatNat", and "Project Kuiper" constellations). In parallel, scientific exploitation of constellations for Earth observation (EO) has also increased in recent years, and with a growing private-sector focus. For example, companies such as Digital Globe and Planet Labs have launched ~300 satellite platforms carrying optical and infrared sensors into low Earth orbit since 2013 (Butler 2014; Hand 2015), and ICEYE operates a constellation of ~14 microsatellites for radar monitoring (www.iceye.com). In the public sector, the European Space Agency's (ESA's) Copernicus Sentinels comprise a constellation of several medium to large satellites to monitor the dynamic Earth system (Berger *et al*. 2012). Prior to these missions, few satellite constellations existed and those that did were operated by international agencies for global positioning systems (GPS) (eg the US-operated GPS and EU-operated Galileo constellations), weather monitoring (eg Meteosat, GOES, and Fengyun constellations) or Earth-system science (eg the A-Train constellation; Berry *et al*. 2019).

In a nutshell:

- The number of artificial objects in space is growing rapidly, driven primarily by an increasing quantity of satellites in low Earth orbit
- Satellite technology can have a range of environmental impacts on Earth, including its use of resources, effects of rocket launches and satellite de-orbiting on the atmosphere, and biological impacts of a changing nighttime sky
- Improved understanding and quantification of these impacts is crucial for evaluating the cost–benefit environmental trade-offs of space-based technology and for identifying ways to mitigate negative impacts

This rapid expansion of human activity in space, hailed as signaling the dawn of a more democratized space age (Butler 2014), raises multiple concerns. These include: negative impacts on amateur and professional astronomical (optical and radio) observations, accumulation of space debris (and associated increased threats to other satellites, spacecraft, and astronauts), collision avoidance with existing debris and other satellites, increased risk of Earth collisions from debris that survives atmospheric re-entry, issues of how occupation of space is regulated (WebPanel 1), and how space activities impinge on human rights (Le May *et al*. 2018; Hainaut and Williams 2020; Rossi *et al*. 2020; Venkatesan *et al*. 2020; Walker

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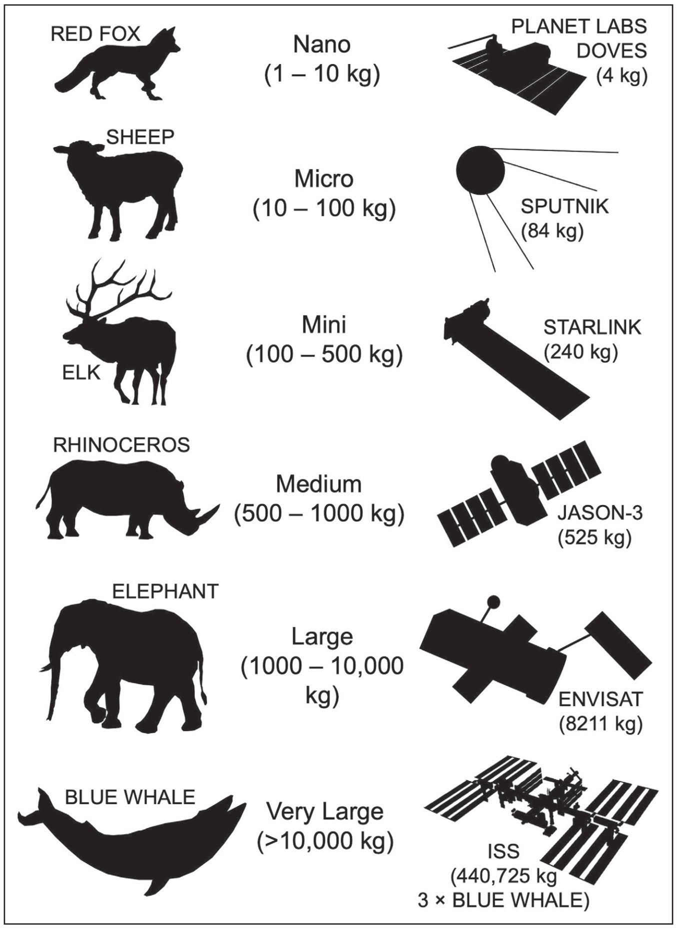

Figure 1. Categories of satellites according to weight with examples of satellites that fall into these categories, and equivalent examples from the animal kingdom. Note that very small categories (femo [<0.1 kg] and pico [0.1–1 kg]) are not shown. Image credit for International Space Station (ISS): NASA/Wikimedia Commons.

et al. 2020; Boley and Byers 2021; Miraux 2021; Sokol 2021). It is also urgent that the emerging geopolitics of this new age of space exploitation be considered critically (MacDonald 2007). The potential for some individual impacts on Earth's environment has been highlighted previously (Dallas *et al.* 2020; Boley and Byers 2021; Sutherland *et al.* 2021), along with their collective influence (Miraux 2021) and the resulting need for evidence-based oversight (Shutler *et al.* 2022). However, attention from ecologists and environmental scientists has been extremely limited, with links between space activities and environmental impacts on Earth not widely evaluated or appreciated. Although typically not of similar orders of magnitude to those arising from, for example, land-use change, climate change driven by increased lower atmospheric carbon dioxide (CO_2) levels, and overexploitation of biological resources, there are indications that in some cases the impacts of increasing human activity in space are, or have the potential to become, both nontrivial and far-reaching.

In this article, we identify major environmental impacts from satellite technology. To facilitate consideration of the range of these impacts, we have structured the text based on a life-cycle perspective, from initial creation of a satellite to its end of life (Figure 2). We also highlight the need to consider carefully the challenging issue of trade-offs between the costs and benefits of satellite technology for humanity and the environment. Much previous attention to the "sustainable use" of space has largely focused on the rather different issues of how satellites are kept operational (without damage from debris) and what the capacity of low Earth orbit is likely to be for satellites (eg Palmroth *et al.* 2021).

Resource use

The building of satellites, launch vehicles, and supporting ground installations is, relative to overall raw material use by humanity, not immensely resource demanding. The commercially sensitive nature of satellite and launch vehicle specifications means, however, that materials and manufacturing techniques involved are not publicly documented, making resource use difficult to monitor and quantify; the raw materials used in building satellites will vary with the payload included and its orbit (which collectively define the satellite power supply system type and size, as well as the structure, propulsion system, and size of the launch vehicle). Nevertheless, most satellites are constructed of aluminum or titanium alloys, or stainless steel, with aluminum preferred and typically constituting up to ~40% of a satellite's mass (Schulz and Glassmeier 2021). When mined and refined, aluminum generates a range of negative environmental impacts (Farjana *et al.* 2019a) and is among the most carbon intensive metals, with a carbon footprint of 12.5 kg CO_2 equivalent (eq) per kilogram (Farjana *et al.* 2019b). Furthermore, manufacturing of satellites and sensors also relies on scarce or rare elements (eg gold, titanium, lithium, gallium), some of which are in increasingly short supply and/or can have major environmental impacts associated with their mining, processing, and recycling. For instance, the collection of lithium used in the manufacturing of batteries has negative environmental and social impacts on ecosystems and communities in the remote Andean Highlands, where lithium salts occur naturally in high concentrations and use of brine-based extraction methods is increasing (Flexer *et al.* 2018). Certain chemicals that can be used in satellite components are also toxic in the natural environment (eg cadmium telluride in solar panels) (Maani *et al.* 2020). These materials are, in the context of their use in satellites, currently impossible to retrieve and recycle owing to fragmentation, dispersal, and subsequent distribution in the atmosphere following de-orbiting and burn-up. However, the overall mass of these rare or scarce elements and compounds within most satellites is relatively small (eg <5% of total satellite mass; Schulz and Glassmeier 2021), and even given the large constellations in existence or planned, the total mass of these materials in orbit will likely remain markedly smaller than within mobile phone, renewable energy, car and aerospace industries.

Launch vehicles require substantially larger quantities of raw materials to manufacture than do satellites, with the booster stages usually being deliberately dropped into the ocean and not recovered. This not only wastes valuable materials but also poses risks to marine life, principally through impacts of debris and contaminants (Lonsdale and Phillips 2021). Reusable vehicles that allow recovery and reuse of some or all of the component stages have emerged in recent years, an example being the retrieval of SpaceX Falcon rockets via barges deployed in the open ocean. However, this reusability is often driven by economics and might not always be environmentally friendly, depending largely on the quantities of additional rocket fuel consumed to maneuver the vehicle components to designated locations and the fuel consumed by marine vessels to recover them (Fridell 2019). Alternative satellite and launch vehicle designs need to be fully assessed in advance of launch, using a cost–benefit analysis that has both economics and the environment at its core.

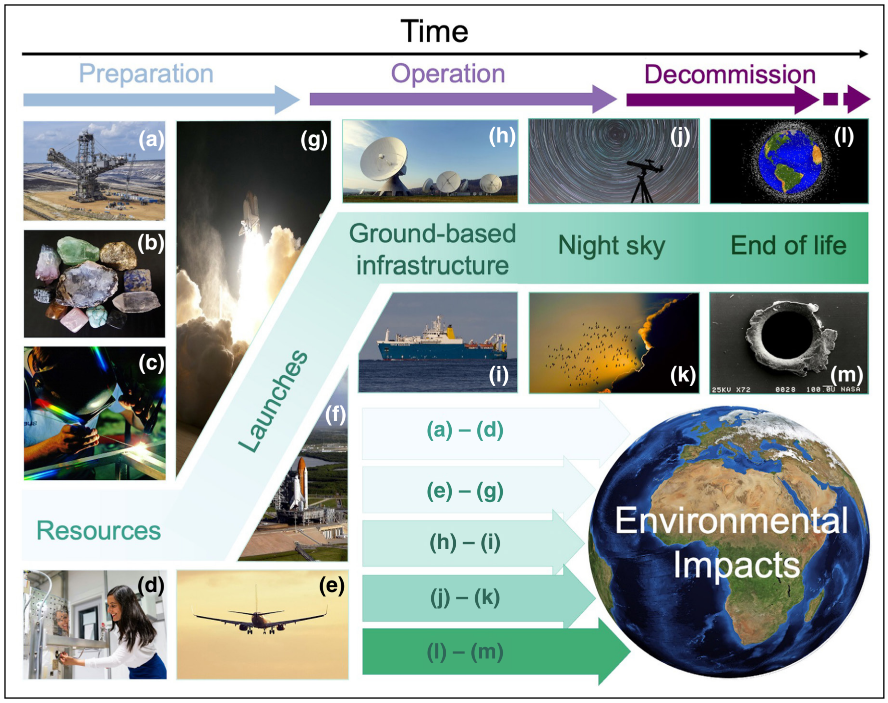

Figure 2. Synthesis figure showing the life-cycle steps and where different environmental impacts occur. Images represent: (a) mining for resources, (b) use of rare earth elements, (c) satellite manufacture processes, (d) satellite calibration facilities, (e) satellite horizontal launch, (f) satellite vertical launch, (g) atmospheric launch pollution, (h) ground segment activities, (i) satellite validation campaigns, (j) night sky brightness impact on astronomy, (k) night sky brightness impact on ecology, (l) increasing space debris, and (m) increasing collisions of space objects. Unless otherwise indicated, all images are from Pixabay. Image credits: (a) 652234, (b) Brett_Hondow, (c) trapezemike, (d) ThisIsEngineering [from Pexels], (e) 5216583, (f) WikiImages, (g) WikiImages, (h) WikiImages, (i) TheOtherKev, (j) astrometeo, (k) mohamed_hassan, (l) WikiImages, (m) WikiImages, and (globe at bottom right) qimono.

Launches

The majority of space activity currently relies on vertical ground-launched rockets, although some organizations have begun to use horizontal launch aircraft, which air-launch a second stage rocket to reach space. Rocket launches inject a host of pollutants directly into all layers of the atmosphere, from ground level to the exosphere at 1000 km altitude and beyond, crucially impacting the atmosphere above the tropopause, where combustion products can reside for years after emission (Ross and Sheaffer 2014). These pollutants include black carbon, aluminum, CO_2, reactive gases, and unburned fuel, with the mix of pollutants governed by rocket engine design, fuel type, and burn profile (Dallas *et al*. 2020). Although historically appearing in low concentrations due to the relatively small number of launches, it has been highlighted recently that the collective impact of these contaminants on the environment should now be considered (Miraux 2021), particularly in light of the large increase in launch rates (Shutler *et al*. 2022). This is because the pollutants can have negative climate impacts in the troposphere (Ross *et al*. 2010); destroy ozone in the stratosphere (Dallas *et al*. 2020); and could promote contraction of the upper atmosphere, impacting satellite orbits (Shutler *et al*. 2022), which, along with lack of a full understanding of the impacts of rocket emissions (WMO 2018), collectively pose risk to the global atmosphere and environment. The changing nature of launch approaches and advancements means that the distribution of contaminants can vary spatially across all layers of the global atmosphere (Lonsdale and Phillips 2021; Shutler *et al*. 2022). The successful development of kinetic launch systems (eg SpinLaunch) for the first stage of launch, with test projectiles so far reaching altitudes of ~100 km, would reduce emissions in the troposphere and stratosphere but would not eliminate rocket emissions in higher altitude atmospheric layers. There is a distinct lack of detailed data on rocket emissions and their volumetric distribution throughout the atmosphere, which prevents parameterization of global atmospheric chemistry and circulation models to query the impact of these activities over different timescales (Ross and Sheaffer 2014). A first step in creating such an emissions dataset could be determined using known launches and published burn profiles (Shutler *et al*. 2022), but the commercially sensitive nature of rocket design and performance, which limits sharing of launch and *in situ* data, would need to be overcome (Shutler *et al*. 2022).

Operational lifetime

Nighttime sky

Environmental concerns regarding satellites during their operational lifetimes have focused foremost on their impacts on human views of the nighttime sky. Low Earth orbit satellites (which commonly have flat polished components) act as point sources of reflected sunlight at night when above the horizon and remain illuminated because of their altitude; the number of detectable satellites declines when the sun is further below the horizon, and is thus a function of time of year and of night (Walker and Benvenuti 2022). At intermediate latitudes, hundreds of satellites may soon be clearly visible to the naked human eye at dark sites (McDowell 2020). There may be two important impacts. First, this may have potential to confuse organisms that use patterns of celestial objects for orientation and migration (Sutherland *et al.* 2021). There is evidence that stellar orientation is used by species of insects, night-migrating birds, and mammals, including strategies based on the center of celestial rotation, the Milky Way, or a lodestar (Foster *et al.* 2018). What influence large numbers of low Earth orbit satellites might have on these abilities is unclear. Rather than their brightness (which is typically exceeded by many stars), the rapid movement of satellites across the night sky is likely to be a key factor, with many vision systems adapted to tracking moving objects such that background stars may in effect become less visible. Second, there are concerns as to what implications a night sky in which increasingly the eye is drawn to human-made objects might have for people's linkages to the natural world. A repeated argument for access to night skies unpolluted by ground-based sources of artificial light emissions has been that this is important for people's sense of place, as well as connection to important cultural roots (Hamacher *et al.* 2019). Presumably this should extend to changes in views of the night sky caused by large numbers of satellites. Notably, native cultures have long histories of cultural engagement with the sky at night. Ethnographic studies have shown that patterns in the night sky have influenced art, navigation, architecture, agricultural practices, and storytelling (Munroe and Williamson 1987; Harris *et al.* 2013; Orchiston 2016). Increased pollution of the night sky for the purpose of providing enhanced internet connectivity to marginalized groups (eg "off grid" first-generation people) has the potential further to sever these groups from their cultural origins, and could be considered a vicarious example of colonization and erosion of native rights.

Growth in numbers of satellites may also have implications for the overall levels of diffuse brightness of nighttime skies. Indeed, this has been estimated already to be as much as 10% above natural levels as a consequence of satellites and space debris (Kocifaj *et al.* 2021); terrestrial infrastructure will contribute further to this increased brightness, although whether this can be differentiated from other ground-based sources seems doubtful. Artificial skyglow (artificial sky brightness) – which is estimated, probably conservatively, to extend over 23% of terrestrial land area (Falchi *et al.* 2016) as a consequence of Earth-bound sources – is likely to have a wide range of biological impacts. This includes through obscuring views of celestial cues for orientation and navigation (Torres *et al.* 2020; Foster *et al.* 2021), providing false cues about time of day and season (Gaston *et al.* 2017), and changing the background illumination against which predator–prey and other interspecific interactions play out (Gaston *et al.* 2021). Many biological processes are, however, sensitive to low levels of nighttime lighting (Sanders *et al.* 2021), including levels below those of skyglow (which, under some circumstances, can be as intense as a full moon), and therefore impacts of skyglow may be far reaching. These impacts could be mitigated. For example, the reflectance of sunlight by satellites can be reduced by altering satellite size, reducing albedo, and modifying orientation or orbit. Although some options have been trialed (Sokol 2021), solutions remain far from operational.

Ground-based infrastructure

Every satellite in orbit is invisibly tethered to Earth during its operational lifetime via terrestrial infrastructure. From launch to burn-up, satellite movement and processes are monitored through a network of facilities, including manufacturing and launch operations, mission control, and ground segment services. The embedded environmental costs of this infrastructure are probably rather high (eg manufacturing of computer hardware, construction materials), and day-to-day operations could have a large environmental footprint, although quantification of this requires deeper synthesis. Recognizing that there is a differentiation in the ground operations required for the wide variety of satellite activities (eg satellite internet services will have a distributed footprint of small receiving stations, whereas EO constellations tend toward larger, more centralized operations), we focus here on EO as an exemplar to highlight infrastructural concerns. Figure 3 and WebFigure 2 illustrate the infrastructure needed to support a generalized EO mission (simplified following Just *et al.* [2014]), demonstrating the extent and complexity of ground operations. Typical EO missions require at least a global infrastructure of ground stations to send and receive data, a mission control center, and a further ground segment support system, within which there is computer hardware for data archiving, processing, and distribution. EO missions also require data captured via *in situ* infrastructure for calibration and validation of data and products over land, in the atmosphere, or in the ocean (WebFigure 2c). Although such calibration and validation data are critical for monitoring sensor

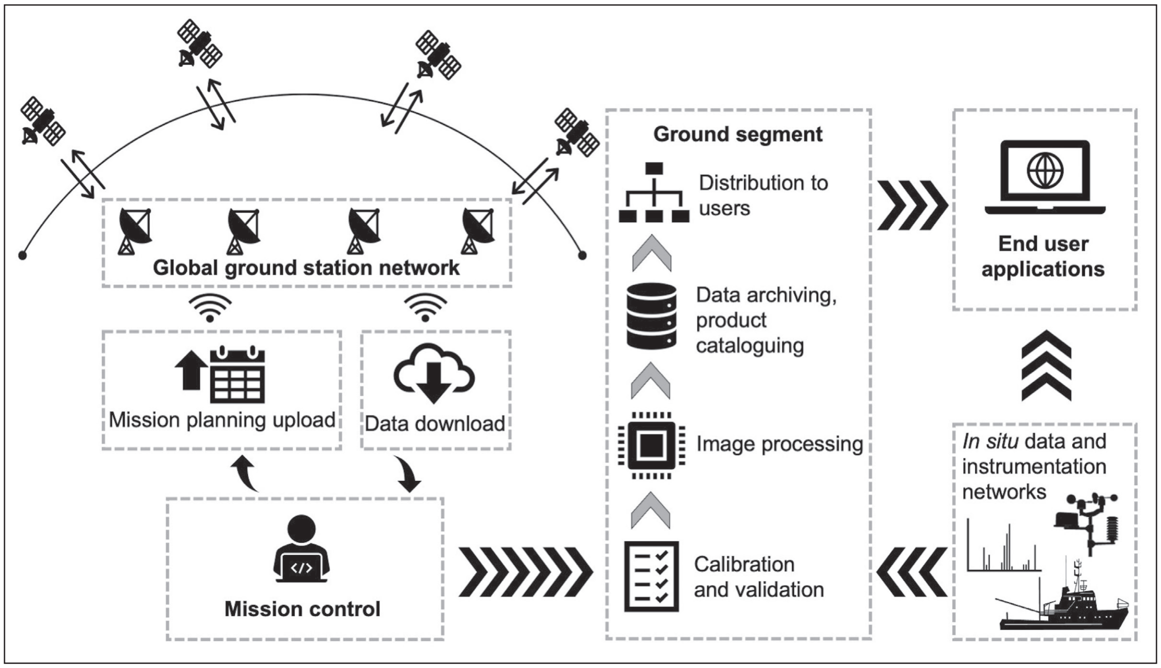

Figure 3. Key aspects of ground-based infrastructure used to support satellite Earth-observation missions. Graphics (clipart) from Microsoft PowerPoint.

performance and ensuring the quality and longevity of data, the environmental impacts of these activities can be high in remote regions (eg oceans, polar regions) (Crossin *et al*. 2020).

Within the satellite EO sector, we also draw attention to recent growth in cloud-driven geospatial analyses. Google has amassed collections of satellite image data captured by the major publicly funded space agencies so that users can process data on the cloud (WebFigure 2e) using the web-based coding platform Google Earth Engine (Gorelick *et al*. 2017). This has revolutionized the way satellite imaging archives can be analyzed because it removes the need for users to run computationally expensive downloading and processing on local machines, thereby speeding up information extraction. There is clearly a huge community of users of this service globally; according to Google Scholar metrics and as of August 2022, more than 5500 scientists have cited the key paper explaining this innovation (Gorelick *et al*. 2017). Google Earth Engine boasts a multi-petabyte archive of imagery, resulting in hundreds of metric tons of CO_2 eq emissions annually just for storing these data (following the rubric shown in WebPanel 2), but given that thousands of users are processing these data and storing resultant products, the actual total emissions will be much greater. These archives can be replicated across different providers – for example, Google catalogues data from both the National Aeronautics and Space Administration (NASA; eg Landsat satellites) and the ESA and EU (eg Copernicus Sentinel constellation). Space agencies will typically avoid keeping all data online to save storage and energy costs, whereas the Google Earth Engine approach requires most data to remain accessible and online within a cloud-accessible data center. Such global data centers currently consume around 200 terawatt hours of electricity, accounting for ~1% of global electricity use (Jones 2018; Masanet *et al*. 2020). As hyperscale models evolve, energy efficiency is improving, which has led to reductions in energy use per gigabyte unit of processing by around 20% annually since 2010 (Masanet *et al*. 2020) – but whether energy efficiency is improving at a rate that exceeds EO data growth, potential storage duplication, and analysis is uncertain. A less well-documented environmental impact of data centers is water consumption for cooling purposes (Mytton 2021). Although it is currently impossible to disaggregate EO data centers from the totality of cloud services, evidence points to a wide range of impacts: for example, data centers with 15 megawatts of computing capacity consume between 80–130 million gallons of water annually (Shehabi *et al*. 2016), and a medium-sized data center uses more water each year than three hospitals or two 18-hole golf courses (Mytton 2021). The environmental and social impacts are exacerbated when data centers are situated in water-scarce regions, such as California. Environmental scientists using satellite data from such data centers and/or processing data on the cloud should engage critically with these impacts of their research, yet this issue has not received detailed consideration within the environmental science literature or within ethical assessments of research praxes.

Decommissioning and end of life

Increasing numbers of satellites will be intentionally deorbited at the end of their operational lives to promote destruction during uncontrolled re-entry, as physical collection or removal is not economic (and indeed currently impossible after retirement of the US Space Shuttle program in 2011). Moving large debris to higher graveyard orbits further away from Earth's atmosphere, where they will remain for hundreds of years, is a current practice, but this too – we argue – is unsustainable, as doing so will ultimately lead to further debris congestion and pollution of space.

Alongside unintentional deorbiting, given the large numbers of – and the relatively short operational lives of many – satellites, intentional deorbiting introduces quantities of material into the upper atmosphere, the majority of which is likely to be aluminum (Schulz and Glassmeier 2021). Concerns have been expressed that this has the potential to damage the ozone layer and, depending on atmospheric residence times, may increase Earth's albedo and reduce warming (Boley and Byers 2021). It could thus result in accidental geoengineering of the Earth's climate (Lawrence *et al*. 2018). Due to the current inability to retrieve orbital objects once in space, the only possible mitigation for debris is to launch fewer, design satellites with longer operational lifetimes, and seek ways to extend the life of existing satellites, thereby reducing the quantity for eventual decommissioning and removal.

Trade-offs

To this point we have focused on the negative environmental impacts of satellites. However, these impacts must be viewed in the context of communication, navigation, surveillance, environmental monitoring, and other benefits that satellite technology provides. These are challenging trade-offs to understand, with considerations that extend far beyond those of science. For example, it is tempting to assume that the comparatively finer spatial and temporal resolution of data provided by constellations of satellites in low Earth orbits is crucial for more accurate environmental monitoring, yet remote-sensing work performed in the 1980s shows that this is not necessarily the case (Woodcock and Strahler 1987). One consideration is the size of objects in the scene relative to the spatial resolution, which results in image classification accuracy varying with two opposing factors. The first is that mixed pixels become more common as spatial resolution coarsens, and therefore finer spatial resolution data can deliver improved classification accuracy. The flip side of this is that increasing spatial resolution delivers elevated spectral complexity per class, reducing not only the spectral separability of classes but also classification accuracy (Markham and Townshend 1981). Consequently, the net result of finer resolution data is not always improved product quality, because the "winner" of these opposing factors will vary depending on the spatial and spectral structures of the environment being studied. The balance between spatial resolution and temporal resolution is crucial for optimizing the design of satellite constellations. Satellite sensors with a wider swath typically have coarser spatial resolution, meaning a larger area can be surveyed during an overpass than with a sensor with finer spatial resolution in the same orbit. Therefore, optimizing these variables can reduce both revisit times and the number of satellites needed for a particular task. Publicly funded space agencies fully evaluate these trade-offs to focus spending of public funds on systems that deliver data to service the greatest number of scientific goals through managing compromises in resolution, swath, and orbital paths. It is not clear whether the same process is followed by commercial space companies, whose goals may differ (eg capturing time-sensitive images for commercial sale); commercial competition may also lead to a proliferation of platforms. We suggest that it is time for a critical appraisal of the information needs of environmental science across public and private organizations, as the environmental costs of remote-sensing data acquisition, storage, and distribution grow.

The provision of internet services from space poses questions about other trade-offs. The major issue is whether space-based internet services offer reduced environmental impacts compared to terrestrial alternatives, such as cabled connectivity and mobile networks. There is an urgent need for studies that quantify and compare the life-cycle impacts of mega-constellations of small satellites and the associated terrestrial infrastructure with those of functionally equivalent cabled and mobile networks.

Conclusions

Given the acceleration in space-based activities, and particularly ongoing and predicted growth in the number of satellites in low Earth orbit, the impacts of artificial space objects on Earth systems need to be considered carefully. There are substantial challenges in understanding the full breadth of these impacts, in determining their relative environmental benefits and costs, and in identifying how best to mitigate the costs. Addressing these issues would be facilitated by a much more open approach from the satellite industry and user community to assessment of environmental impacts, from initial conception through decommission (including any lifetime extensions), and to provide evidence of environmental net gain prior to launch.

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Data Availability Statement

No data were collected for this study.

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