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An astro-green criminological examination of orbital space debris

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Abstract

The aims of this study were to (1) highlight the importance of orbital debris as an environmental and green criminological issue, (2) build on recent work in astro-green criminology and (3) analyse orbital debris from an astro-green perspective with a focus on social and ecological harms consistent with green-critical criminologies. Human-made active and defunct debris continues to accumulate in Earth orbit littering near-Earth orbital space. There are a small number of key drivers, including accidental collisions between objects, in-orbit explosions and anti-satellite missile testing. Such activities pollute Earth orbit causing problems for astronomy, space travel and human and non-human populations on Earth. This is a theoretical, literature-based analysis of orbital debris from an astro-green criminological perspective. Criminology has had little to say about space debris because its creation is not a criminal offence. This article makes a unique contribution to criminological literature by applying the emerging perspective of astro-green criminology to orbital debris.

Keywords

Astro-green criminology, green crime, green criminology, orbital space debris

Introduction

While the environmental crises of climate change and biodiversity loss are topics of criminological inquiry, criminology has yet to sufficiently turn its gaze beyond planet

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Earth. The primary aim of this article is to further address this oversight by highlighting current problems regarding anthropogenic space debris in Earth orbit and critiquing this from an astro-green criminological perspective. Despite important implications for the environment and public health, the accumulation of human-made objects in Earth orbit is an issue that has barely received any recognition in the criminological literature (for some minor exceptions, see Carrabine, 2018; Lampkin, 2021; Takemura, 2015 and Wyatt, 2016).

A further aim of this article is to direct criminological scrutiny towards a previously unconsidered research area (space debris), whereby escalating levels of human activity risk serious environmental consequences for terrestrial and extraterrestrial settings, and for future generations of humans. Consequently, this article will draw the attention of the criminological and, more specifically, the green and critical criminological communities; and will initiate an area of study that seeks to build an understanding of the nature of human actions that lead to the accumulation of orbital space debris (OSD). Without legal and criminological engagement with this issue, debris accumulation will continue unchecked and unchallenged. This presents risks to future space-related activities and space exploration through the inability to safely launch rockets and satellites into space. Furthermore, the continued accumulation of matter in Earth orbit creates a dangerous LEO[1] region where debris could impact the functioning of important satellites that are vital for the functioning of everyday life. As Pelton (2015: 1–2) denotes,

> Space systems have become so very vital, that if we were suddenly denied access to our space-based infrastructure for weather forecasting and warning, for space-based navigation and timing, for civil and military communications, and for remote sensing and surveillance from space we would be in danger. We would suffer almost immediately – economically, militarily, and socially. Many of our transportation and communications systems would go down along with our weather and rescue services and defense systems. Internet would . . . (lose) its synchronization, credit card validation would no longer work, we would not be alerted to major storm systems, air traffic control, shipping navigation, and trucking routing services would be lost.

We argue that criminologists and, in particular, *green* criminologists should be concerned with OSD because such items constitute a form of litter and space junk. Groombridge (2013: 396) helpfully imagines litter as a continuum ranging 'from the accidental individual littering incident to widespread deliberate organized transnational pollution'. This conceptualisation of litter places OSD at the latter end of the continuum, as debris creation is always the result of the actions of nation states or large corporations (such as SpaceX and BlueOrigin). Although there are national policies and regulations that attempt to mitigate the impact and build-up of OSD, such as the *Inter-Agency Space Debris Coordination Committee's Mitigation Guidelines*, there is no legally binding international framework that prohibits debris formation or punishes polluters for contributing to the orbital debris population. Consequently, orbital litter continues to accrue in Earth orbit with no consequences for contributors.

Carrabine et al. (2020: 3) loosely define *criminology* as the study of 'crime, criminals and criminal justice'. Although criminological definitions are contested (Wolfgang, 1963), *crime* is, perhaps unsurprisingly considering the discipline name, almost always a feature of criminological definitions. This means that a core focus of mainstream criminology is both crime and criminal justice systems. Due to this fixation on the criminal law, and the absence of a formal criminal mechanism for managing OSD, it is green and critical criminologists who are best placed to study space junk. This is because critical criminologists take a zemiological approach to the study of criminology, where both crime and social harm are considered useful to the study of 'socially injurious behaviour' (Schwendinger and Schwendinger, 2013: 115). This thought is shared by Green and Ward (2004: 4) who consider criminology to be the 'study of deviance and social control'. Green criminology emerged out of the longer established paradigm of critical criminology (Sollund, 2021) and focuses specifically on environmental harms as well as crimes (Lampkin, 2020). Therefore, if one is to conceptualise OSD as a form of harmful litter that develops in the absence of formal criminal mechanisms, this falls comfortably within the remit of a *green* criminology: the study of 'crimes, harms and offences related to the environment, different species and the planet' from an interdisciplinary, open and evolving perspective (Brisman and South, 2020: 40).

This article will debate these issues using the following structure: Introducing astro-green criminology; Sources of OSD; The marine impacts of debris re-entry; and Applying AGC to OSD.

Introducing astro-green criminology

Although it is well recognised that academic engagement with environmental problems well preceded the emergence of a specifically *green* criminological perspective (Goyes and South, 2017), green criminology has been influential in exposing instances of environmental harm since its conception. The term 'green criminology' was coined by Michael Lynch in 1990 'at a time when people were becoming increasingly troubled about large-scale environmental disasters' (Lynch et al., 2017: 2). Due to the narrow concentration of orthodox criminology on distinctly criminal behaviours only, green criminology emerged as a response to the failing of mainstream criminologists to take environmental harms seriously. This is because many environmentally destructive practices were – and still are – *lawful*. Green criminologists fill this academic void by researching human behaviours that are both legal and illegal. The justification being the fact that environmental laws and regulations often fail to prevent environmental harms, and much destructive behaviour continues within society unabated. As such, green criminology fits well with other criminological offshoots that critique this crime-harm nexus, such as zemiology (Brisman and South, 2018) and critical criminology (Sollund, 2021).

Astro-green criminology (AGC) is a perfect example of a criminological sub-discipline that has arisen as a result of this complex crime-harm relationship and is best situated within the green-critical criminological paradigm. The term was only coined very recently, by Takemura (2019) in his pioneering work on *Space Capitalism*. This article can be seen as an extension of Takemura's (2012, 2015) earlier work on OSD, and these were the first two texts to discuss outer space and green criminology in unison. Since then, a few key publications (Lampkin, 2021; Lampkin and Wyatt, 2022) have emerged expanding on the notion of AGC, adding to Takemura's seminal works.

One of these publications offered the very first definition of AGC. This was explicated as

> the theoretical and practical study of space-related environmental harms and crimes that are facilitated by human actions. These harms can be Earth-based, atmospheric, or extraterrestrial and may create human victims, non-human victims, and ecological victims both on Earth and in outer space. (Lampkin, 2021: 242)

While definitions are often critiqued, they can also provide a starting point from which to theorise, problematise and debate a new perspective or area of study. It was from this basis that Lampkin (2021) expanded the remit, purpose and subject area of AGC. This was done by, following the first definition of AGC, providing an outline of what some of the key issues are. Specifically, Lampkin (2021) identified five quintessential areas which were OSD, extraterrestrial mining, space industry–related emissions pollutions, the protection of heritage sites on celestial bodies and the future usages of outer space that could have an environmental impact (such as space travel, tourism or colonisation). However, Lampkin (2021) only provides brief analysis of these areas to lay the foundations of astro-green areas of study. As a result, this article expands on these foundations, critiquing only one issue, orbital space debris, in significantly more detail.

Sources of OSD

OSD refers to 'any object in Earth orbit that does not have a useful purpose' (Australian Space Academy, 2010: no page) such as defunct satellites and fragments from previous in-orbit collisions (Pelton, 2015). Prior to the launch of the first artificial satellite *Sputnik-1* in 1957, there were no human-made objects orbiting Earth. Today, humans have lost track of the number of items in Earth orbit.

There are a vast number of individual pieces of debris currently orbiting the Earth, many of which are extremely small. The exact number of pieces is currently unknown because objects smaller than 10–20 cm are not usually catalogued (Chobotov, 2002), creating an unknown – *dark figure* – of OSD. This has led to the LEO region being described as 'the World's largest garbage dump' where 'close to 6,000 tons of materials occupy the area' (National Aeronautics and Space Administration (NASA), 2019a: no page). Of this debris, the majority is no longer of any use to humans and continues to orbit Earth due to the expense involved with collecting or destroying it. In addition, there is a complete absence of binding law regarding the clean-up of existing OSD, and a lack of a law enforcement presence requiring its removal. As a result, much of the anthropogenic matter in LEO now serves no useful purpose. As Stakem (2018: 6) suggests, 'of the 7,000 or so satellites placed into Earth orbit so far, 1,500 are still functioning. The rest are zombie-Sats'. Although pollutions of varying kinds on Earth have been subject to much green criminological scrutiny in recent years, including problems surrounding litter (Groombridge, 2013) which has close connections to OSD, the issue of anthropogenic pollution in outer space remains virtually unexplored within criminology.

Anthropogenic matter accrues in Earth orbit for a variety of different reasons. As Stakem (2018: 5) recalls, 'known space debris includes Astronaut Ed White's outer glove, lost on his spacewalk; Michael Collin's camera from Gemini-10; a wrench, pair of pliers, and a toothbrush'. These items are clearly the result of humans physically occupying Earth's orbit in space stations. However, most OSD is the result of a small number of major satellite collisions ensuing from the 'catastrophic destruction of three intact satellites (Fengyun-1C, Cosmos-2251 and Iridium 33)' (Pardini and Anselmo, 2017: 23) (see Table 1). These events alone increased catalogued orbital debris by approximately 50% (Pardini and Anselmo, 2013).

Despite the enormous impact of these collisions on the accumulation of OSD in Earth orbit, there have been several other significant collision events, which usually take place every 5–9 years (Stakem, 2018: 5). To demonstrate the contribution of these events to the accumulation of OSD, Table 1 categorises both the specific event and the approximate amount of debris generated according to academic literature.

Table 1 presents a compilation of the most catastrophic and commonly cited debris creation events within academic literature. However, it does not represent every debris-creating event and, therefore, many more pieces of debris exist that are not quantified in Table 1.[3] This is because only objects of at least 10 cm are documented by the US Space Surveillance Network (SNN)[4] fragment cataloguing process (Wang, 2010: 89). Nevertheless, objects and particles smaller than 10 cm still represent a major threat to existing active satellites, spacecraft and space stations. This is because the size of an object has little impact on the speed with which it orbits and so even small objects can collide with enough force to cause a damaging impact, due to their high speed of travel. As Truitt and Hartzell (2020: 876) suggest, sub-centimetre 'orbital debris is currently undetectable using ground-based radar and optical methods. However, pits in space shuttle windows produced by paint chips demonstrate that small debris can cause serious damage to spacecraft'. Thus, while Table 1 highlights *some* of the major events that have resulted in a large quantity of debris creation, it only establishes part of the overall picture of debris creation.

What Table 1 does demonstrate effectively, though, is that OSD is generally attributable to a small number of causes. These include accidental collisions between existing satellites, the intentional destruction of satellites (ASAT testing) and other unintended events (such as malfunctions, break-ups and explosions). To more thoroughly understand OSD, it is pivotal to explore these issues in further detail.

Accidental collisions between existing satellites are extremely rare, to the point that only one catastrophic event has ever occurred. This was between the Cosmos-2251 and Iridium-33 satellites in 2009. While unintentional, this event created a massive amount of OSD and highlights the imperfect nature of human scientific and technological endeavour. Accidental collisions with existing orbital debris are more frequent, in part because of the significantly greater number of pieces of debris compared with that of artificial satellites. Furthermore, it is much more difficult to alter the direction of a piece of debris or defunct satellite, as opposed to a functioning satellite where the orbit can be remotely adjusted to avoid a potential collision (Welti, 2012). However, the intentional destruction of satellites may represent an even more serious problem in terms of OSD, as well as in terms of space warfare and weaponization.

To date, the intentional destruction of satellites is more common than two satellites colliding accidentally. Table 1 highlights the four countries known to have engaged in

Table 1. Significant events creating OSD.

Year	Major event creating orbital debris	Source	Original quantity of debris generated
1962	'An early satellite experiment involving the intentional creation of space debris was "West Ford," a 1961–62 program involving the launch of some 350 million short copper filaments into an orbital belt, in an attempt to produce an artificial ionosphere which could be used for reflecting microwave transmissions over long distances' (Swenson, 1985: 71).	Experiment	350 million short copper filaments.
1968–1985	The Soviet Union conducted at least 20 anti-satellite (ASAT)[2] tests in this period (Shackelford, 2014), but in 1987 (along with the United States), they signed the Intermediate-Range Nuclear Forces Treaty to eliminate missiles with ranges of 5000–5500 km after 8 years of negotiation (Druckman et al., 1991). Recently, Russia has failed to abide by the terms of the treaty, leading to its demise when the United States withdrew in August 2019.	Russian ASAT tests	Not quantified.
1985	A US ASAT test was 'used to destroy an aging US weather satellite' creating orbital debris that took 19 years to burn up in Earth's atmosphere (Krepon and Black, 2009: 22).	US ASAT test	300 pieces of trackable debris (Krepon and Black, 2009), but possibly 'thousands of pieces of greater than 1 cm' (Stakem, 2018: 5).
1996	In June 1996, the small Pegasus launcher exploded. Pegasus was an Ecuadorian cube satellite that originally stopped working after colliding with debris 'from fuel containers of rocket S14, launched by the Soviet Union in 1985' (Yulin and Zhaokui, 2015: 1189).	Collision and explosion	Added 700 observable objects increasing debris in the '600 km altitude by at least a factor of two' (Schildknecht, 2007: 49).
2007–2012	In February 2007, the Briz-M satellite exploded creating c.1000 pieces of debris. A similar event occurred in 2010 and again in 2012. Briz-M refers to a type of Russian rocket which became stranded in orbit with fuel on-board (Hall, 2014).	Explosions	Originally 1000 fragments were detected, but only 92 catalogued (Liou and Anz-Meador, 2010). In the 2012 explosion, '700 large debris' were detected (Matney et al., 2013: 2).

(Continued)

Table 1. (Continued)

Year	Major event creating orbital debris	Source	Original quantity of debris generated
2007	Similar to the US ASAT test of 1985, China intentionally destroyed a non-functioning weather satellite (Fengyun-1C) as part of their own ASAT test. It has been suggested that 'most of the Fengyun-1C debris will stay in orbit for several decades; some is expected to remain in space for centuries' (Liemer and Chyba, 2010: 149).	Chinese ASAT test	917 pieces of debris 10 cm or greater. Tens of thousands of pieces too small to track (Lieggi and Quam, 2007: 21).
2008	The Cosmos-2421 Satellite broke apart in three significant events between March and June 2008, the reasons for which are still unknown (Reddy et al., 2011).	Unknown breakup of satellite	Approximately '500 large debris and an unknown number of smaller debris' (NASA, 2008: 1).
2009	In February 2009, a defunct Cosmos-2251 Russian Satellite collided with the US Iridium-33 satellite which represented 'the first accidental catastrophic collision between two intact objects' (Anselmo and Pardini, 2009: 1).	Accidental collision between two satellites	Approximately '8 million fragments smaller than 1 cm in size were formed, but only about 1,800 were catalogued' (Adushkin et al., 2020: 4).
2019	In March 2019, India intentionally destroyed one of its own satellites, Microsat-R. Tan et al. (2020: 3) found that 'several hundred fragments spread . . . into higher orbits,' preventing them from burning up in Earth's atmosphere.	Indian ASAT test	83 new fragments were registered as a result of the ASAT test (Akhmetov et al., 2019), but as many as 400 were originally identified by NASA (2019b: 1).
2021	In March 2021, China's YunHai 1–02 meteorological spacecraft accidentally collided with a piece of debris that originated from the deployment of a Russian launch vehicle from the Cosmos-2333 spacecraft in 1996.	Accidental collision between debris object and satellite	37 new trackable fragments created, four of which decayed very quickly (NASA, 2021).
2021	In November 2021, shortly before the attempted invasion of Ukraine, Russia intentionally destroyed their own satellite Kosmos-1408.	Russian ASAT test	'At least 1,500 pieces of trackable debris' (Wang et al., 2022).

NASA: National Aeronautics and Space Administration.

anti-satellite testing thus far: Russia and the former Soviet Union, the United States, China and India. ASAT capability is important in terms of the accumulation of space debris, but also from a criminological viewpoint. This is because ASAT technology presents powerful governments and organisations with the ability to drastically impact satellites from another nation who may rely upon them as part of their critical infrastructure, military or otherwise. Therefore, ASAT missiles serve as a powerful political tool due to the potentially severe consequences of satellite destruction as depicted by Pelton (2015) in the introduction.

Despite such risks, intentionally destroying another nation's satellite would be viewed as an act of aggression and could result in counter measures against the instigating country (such as a retaliatory attack on its own satellites), which arguably lessens the likelihood of future targeted ASAT missile attacks. However, while such weapons remain a potential threat, it is likely that other global powers will look to achieve a similar level of capability, both to maintain a strong conflict deterrent and to avoid being at a strategic disadvantage should such conflict occur (in much the same way that nuclear weapons can be seen to act as a deterrent). Hence, it is likely that the current proliferation of advanced space weapons will continue. This may explain why ASAT testing is still a feature of contemporary human society, despite the Intermediate-Range Nuclear Forces Treaty (see Table 1). ASAT testing, therefore, is not solely of interest to green criminologists studying environmental harms and crimes, but also to criminologists studying crimes of the powerful (Tombs and Whyte, 2003) and war crimes (Grčar, 2018).

Other than collisions and ASAT testing, Table 1 pinpoints other debris-creating events deriving from technological failure. These include malfunctions, the unknown 'breakup' of satellites and explosions. Mission-related debris, such as leaving payloads and rocket bodies[5] in orbit after their useful life, also contributes a significant amount to OSD (Kessler et al., 2010). While the exact amount is unknown, recent calculations suggest that the total mass of space objects in Earth orbit totals more than 6000 tons (NASA, 2019a) and consists of over 128 million objects of 1 mm or greater (European Space Agency, 2020b).

One fear of such dramatic increases in OSD is Kessler syndrome. This is the theory that OSD may become a chain reaction whereby more debris means a greater probability of accidents and collision events, leading to evermore debris pieces and a 'cascading chain activity' (Larsen, 2018: 475). This could eventually create an impassable debris belt that obscures the night-sky for astronomers and renders space travel impossible. However, Kessler syndrome is not the only concern regarding OSD. Large objects sometimes reenter Earth's atmosphere posing a risk to humans (if land is struck), or marine environs (if a splash-landing occurs).

The marine impacts of debris reentry

Large objects that do not burn up in Earth's atmosphere must crash down somewhere. *Point Nemo* (or *the pole of inaccessibility*) is the point on Earth farthest from any Island and, therefore, the most remote and least likely place to have a human impact. As a result, when re-entering the atmosphere, this is the safest place to aim for to safeguard human life.

Point Nemo has accumulated over 260 pieces of space debris, including the remains of several space stations (Stakem, 2018). These splashdowns clearly generate moral and ethical concerns pertaining to the anthropogenic use of Earth environments for outer space exploration and as a location for debris disposal. Furthermore, they pose challenging legal questions. Point Nemo, for instance, is part of the *high seas*, far from the jurisdiction of any nation. Therefore, there is no legal responsibility or international law requiring a nation or private company to clean-up space junk that lands there. As a result, Point Nemo has been colloquially dubbed the *space cemetery* in acknowledgement of the final resting place of dead satellites, spacecraft and other large OSD (De Lucia and Iavicoli, 2019).

Such space debris reentry is problematic for a variety of reasons. First, it poses a risk to the aviation sector as the object races towards Earth's surface. Second, when it gets there, marine vessels are in jeopardy of being struck. These are described as *kinetic risks* by De Lucia and Iavicoli (2019: 369–370) due to the debris experiencing motion as it moves through Earth's atmosphere. It is important to note that small changes in the descent trajectory of large objects, while far above the Earth, can change the final landing location by many hundreds of miles. Consequently, reentry needs to be meticulously planned and executed. Even so, operations do not always go as planned.

There are also other potential environmental implications for end-of-life reentry of OSD. An obvious implication is the impact that material burnt up upon reentry may have on Earth's atmosphere. A further consequence results from the larger pieces of debris that do not fully burn up and therefore contaminate environments on Earth's surface. It has already been suggested that large object reentry is relatively rare as a proportion of the total mass of debris objects re-entering the atmosphere. However, when this does occur, it has the potential to have a large environmental impact. This is best demonstrated through a series of events provided in Table 2.

As with Table 1, Table 2 does not represent a complete list of all large object re-entries. It does, however, provide an account of the most cited re-entries in the academic literature which serves to highlight the scale of the problem. Although these events are unlikely to create human casualties, they do present a risk to human life, particularly in uncontrolled events. Furthermore, the chemicals aboard large objects present a threat to human and non-human life. As Luchinski et al. (2003: 665) highlight,

> A danger to people and property on the ground is present in an uncontrolled reentry of large-scale objects and objects containing incombustible, heat-resistant, or hazardous (e.g. radioactive) materials. The large size of a spacecraft means that large pieces of it would survive any reentry and impact Earth, endangering people.

The impacts of OSD on Earth orbital and marine environments demonstrate the connection between OSD issues and green criminology.

Applying AGC to OSD

Takemura (2012, 2015, 2019) is the only author to have discussed space debris from a criminological perspective in any significant detail. However, there has been some other (albeit limited) criminological engagement. For example, South (2017) has recognised that pollution of Earth's atmosphere does not just stop at fossil fuel combustion,

Table 2. Case studies of significant large object reentry events creating pollution.

Year	Large debris object	Reentry type	Event
1978	Cosmos-954 Satellite	Uncontrolled following satellite malfunction	The Cosmos-954 satellite launched by the USSR in 1978 (and carrying a nuclear reactor containing uranium-235), was intended to orbit Earth for a few weeks before being raised to a higher orbit (a feat successfully achieved by the Cosmos-952 satellite previously). Unfortunately, Cosmos-954 malfunctioned and was drawn by gravity towards Earth, eventually disintegrating and scattering radioactive debris over northwest Canada (in an area the size of Austria) (Galloway, 1979: 401–402).
1979	Skylab Space Station	Uncontrolled	In July 1979, the 80 megaton Skylab space station 're-entered and rained debris in a footprint more than 1,000 km long and nearly 200 km wide in southwest Australia' (Luchinski et al., 2003: 665).
1991	Salyut-7 Space Station	Uncontrolled	In February 1991, the 43 megaton Salyut-7 Space Station 'made an uncontrolled reentry over Argentina' (Luchinski et al., 2003: 665). Despite much of the debris landing near the town of Capitan Bermudez (approximately 190 miles from the Capital Buenos Aires), there was no loss of life or property damage reported (Powell, 2017: 167).
1996	Mars-96 (Russian Orbiter and Lander)	Uncontrolled following failed Mars mission	Initially intended to orbit and then land on Mars to conduct scientific experiments, the 'rocket carrying Mars-96 lifted off successfully, but as it entered (Earth) orbit the rocket's fourth stage ignited prematurely and sent the probe into a wild tumble. It crashed into the ocean somewhere between the Chilean coast and Easter Island. The spacecraft sank, carrying with it 270 grams of plutonium-238' (Garber, 2015: 1).
2000	NASA's Compton Gamma Ray Observatory (CGRO)	Controlled	In June 2000, NASA's 17 megaton CGRO splashed down 'over a region in the Pacific Ocean southeast of Hawaii' (Luchinski et al., 2003: 665).

(Continued)

Table 2. (Continued)

Year	Large debris object	Reentry type	Event
2001	Mir Space Station	Controlled	Launched in 1986, Mir replaced the Salyut series until it was de-orbited in 2001. Of the original mass of 130 megaton, approximately 40 megatons survived reentry, breaking up at various levels of altitude (Luchinski et al., 2003: 665). Those pieces of debris that survived reentry were either large enough to avoid burn up in the atmosphere, and/or consisted of material with very 'high melting temperatures including steel, titanium, high-temperature alloys, illuminators, and optical equipment lens' (Luchinski et al., 2003: 665).
2011	Upper Atmosphere Research Satellite (UARS)	Uncontrolled	UARS was a NASA satellite deployed in 1991 to study ozone depletion in the Antarctic region. Prior to being decommissioned, it was hit by a piece of existing orbital debris in 2007 creating new debris (Yulin and Zhaokui, 2015). In 2011, it re-entered Earth's atmosphere landing in the Pacific Ocean and, of the original 5668 kg of dry mass, 'a total surviving mass of 532 kg concentrated in 26 objects (survived reentry). The heaviest surviving component, an aluminium box, had a mass of 158 kg' (Pardini and Anselmo, 2012: 4).
2011	ROSAT Satellite	Uncontrolled	One month after the UARS splash-landing, a German x-ray satellite, Roentgen Satellite (or ROSAT), crashed into the Bay of Bengal near the populated countries of India and Bangladesh. ROSAT was about half the size of the UARS with a dry mass of 2426 kg (Choi et al., 2017).
2012	Phobos-Grunt Spacecraft	Uncontrolled	Originally intended to study one of Mars' moons (Phobos), the Phobos-Grunt 'spacecraft failed to exit the Earth's orbit and fell into the Pacific Ocean' (Durrieu and Nelson, 2013: 242). Phobos-Grunt was carrying 'about 11 tons of unused highly toxic propellant' (Durrieu and Nelson, 2013: 242).
2020	Long March 5B Rocket	Uncontrolled	After 1 week in LEO, the core of the rocket made an uncontrolled reentry. The majority of the (approximately 20-ton) core crashed into the Atlantic Ocean off the coast of Africa; however, some debris fragments were found scattered across the Ivory Coast (Maley, 2020).

USSR: Union of Soviet Socialist Republics.

deforestation and industrial activities, but extends to wastes left in human orbit. Similarly, when discussing the impact of hazardous wastes on future generations, Wyatt (2016: 2) considers space debris as a problem that we are only just beginning to experience, but one that will continue to cause problems ‘unless active removal programmes are undertaken’. Carrabine (2018: 455) has also recognised the impact of space debris on future generations:

> Since the 1960s, hundreds and thousands of objects have been launched into space, many of which are now defunct but are destined to stay there as a belt of debris. This distant layer of debris will become the major ruins of our times, potentially drifting around the Earth for billions of years, outlasting the great pyramids of Giza and the cave paintings of Lascaux.

Lampkin (2021) went further than these works by explaining the link between space debris and criminology, suggesting OSD would be one of the primary areas of study for AGC research.

This article not only suggests that space debris is a problem worthy of criminological attention, but it makes a significant contribution to the (astro) green criminological literature. Table 3 identifies six key areas of focus for green criminologists regarding the issue of OSD, the aim of which is twofold. First, it identifies some of the key problems attributed to OSD with a specific focus on both human and non-human harms and victimizations. Second, it provides a structure and six areas of focus for any future astro-green criminological work in this area.

It is clear from Table 3 that only a critical or radical criminological perspective could adequately address the harms associated with space debris because they are legal activities. While some institutions and organisations have produced guidelines intent on preventing and mitigating against the accumulation of debris (such as NASA’s (2018) *Handbook for Limiting Orbital Debris*), these are not legally binding. Furthermore, although there have been several important developments in international space law such as the Outer Space Treaty (OST) of 1967 and the Committee on the Peaceful Uses of Outer Space (COPUOS) established in 1959, these deal ‘almost exclusively with political and diplomatic issues, which is reasonable as. . . (they) were written during the Cold War’ period (De Paula and Celestino, 2019: 1). Consequently, they have been criticised as outdated and unfit in dealing with contemporary OSD accumulation issues (Ferreira-Snyman, 2013).

The problems surrounding both preventing and disposing of orbital debris can therefore be seen as issues that lack ‘political, legal and economic’ will (Stakem, 2018: 23), rather than technological impossibilities. As a result, it can be argued that Earth orbit has thus far been regarded by humans as a frontier to exploit, rather than a wilderness to protect (Takemura, 2019). The lack of legal accountability and enforcement of guidelines for creating and removing OSD should be a concern to criminologists due to the impacts that debris can have on humans, non-human animals and ecosystems, as outlined in this article. Until more substantial international laws and enforcement practices are implemented, OSD will continue to accrue. Criminologists could play a vital role in instigating such discussions and building a body of academic research calling for more to be done to protect planet Earth from the build-up of anthropogenic orbital pollution.

Table 3. The harms of space debris.

Human harms	Non-human harms
Humans in Space Orbital debris presents risks to humans who inhabit off-Earth space stations. Debris may strike the station (Truitt and Hartzell, 2020), tear an astronaut's spacesuit (Castronuovo, 2011), or otherwise damage essential equipment.	Oceanic Environments Large objects that re-enter Earth atmosphere are targeted at oceanic regions (such as Point Nemo). Therefore, orbital debris presents a hazard for marine life and ecology, particularly if it contains wastes or hazardous substances that could harm marine life (De Lucia and Iavicoli, 2019) or enter the food chain.
Humans on Earth Pieces of debris that too large to burn up in Earth's atmosphere present a threat to human life and property (Durrieu and Nelson, 2013). This is particularly concerning for uncontrolled re-entries that may impact land rather than ocean (Luchinski et al., 2003).	Atmospheric Harm Launching spacecraft and satellites (that may one day end-up as orbital debris) involves atmospheric pollution through emissions of harmful chemicals into various stages of the Earth's atmosphere (Ross and Vedda, 2018). Harmful elements are also generated when debris re-enters the atmosphere, most of which burns up creating chemical and radiological risks (De Lucia and Iavicoli, 2019).
Future Generations of Humans The more orbital debris generated, the greater the problems become for future generations of humans in terms of continued space exploration, but also in terms of the above two points (risks to humans in space, and humans on Earth, from reentry events).	Higher Orbit Pollution High Earth orbits are problematic because debris may reach a height where it will not re-enter the Earth's atmosphere (and will therefore continue to orbit indefinitely). The more of this type of debris generated, the more problematic it becomes to dispose; and the more challenging it becomes to engage in future space exploration.

It is clear that the natural sciences (engineering, physics, cosmology) have placed a greater priority on the commercial development of Earth orbital space than they have on prevention, mitigation and removal strategies. This is due to the continued mass accrual of OSD in Earth orbit and a failure, thus far, to address the issue. Consequently, the critical and green criminological traditions are particularly well placed to lead discussions relating to the human and environmental impacts of OSD, and this is the best place for an AGC to be situated.

There are a number of reasons for this. First, as has been noted, green-critical notions of crime are rooted in a zemiological paradigm where social and ecological harm is observed to be a more inclusive way to approach unwanted deviant behaviours (as opposed to purely criminal notions that are customary in the classical criminological tradition). Second, green-critical criminologists emanate from a place that is usually far removed from academics and practitioners working in the natural sciences. As such, the focus of an astro-green criminologist is not foremost on the technicalities of rocket launching or satellite capability, but on the impact that those activities have on both social life and the natural world. The impact of space exploration and satellite technologies has historically been construed from the effect that it may have on other technologies and other satellites, and how this might impact future technological successes. An example is the historical focus placed by the space exploration community on managing and manoeuvring objects within and between orbital spaces, rather than assessing the impact that the activities are having on human life, atmospheric health and ecological conditions on Earth's surface (for instance, those harms outlined in Table 3).

Consequently, green-critical (or astro-green) criminologists can use their expertise in social research to contribute to OSD discussions, filling the current void in the social, atmospheric and ecological impacts of rocket launching and satellite technologies. Contributing to the research and debate on orbital space debris from this critical research mindset may help to inform the future policy directions of orbital debris prevention and mitigation. Doing so is, arguably, in the best interests of both public health and ecosystems, and also the scientific community. In terms of the former, astro-green analysis of OSD will give a voice to human and non-human victims (see Table 3), concerns for which may have otherwise been ignored at best, or not brought to the table at worst. In terms of the latter, the scientific community have much to gain from the inclusion of criminologists. Successfully preventing, managing and mitigating OSD will, inevitably, contribute to a safer and cleaner orbital environment for current and future generations.

Conclusion

This article has highlighted the harmful effects of OSD, issues which have received scant attention from the scientific community, and virtually no attention from the criminological community. It is clear, however, that OSD is a social phenomenon worthy of greater academic consideration due to the risks posed to humans and non-humans.

Like many human scientific and industrial endeavours, the formation of space debris appears to have accrued *despite* the harmful consequences, rather than instigating precautionary and preventive measures at the outset. At some point, we (as humans) will need to prevent or recycle debris rather than disposing of it in graveyard orbits or oceanic environments. Currently, OSD can be seen as a self-created nuisance for the space industry, produced by a series of significant events that have exponentially increased the number of pieces of debris (see Table 1). However, due to the expense associated with debris mitigation, 'we probably won't see any action until there is a "major event"' (Stakem, 2018: 23). Debris capture and reuse is an expensive mitigation option for what is already a costly industry, often relying heavily on public money. Therefore, the initial prevention of debris formation may be the most effective approach to address the problem.

Finally, this article has argued that orbital debris is a concern for green criminologists due to the harms associated with its creation. However, the astronomical community should also be concerned with the environmental impact of space operations, including the generation of space debris, because it is in their best interests. As Andersen (2000: 443) suggests, 'accelerating man-made degradation of the environment is making the sky and astronomical objects harder to see. Light pollution, radio frequency interference, space debris, and activities in outer space are restricting astronomy, remote sensing, and telecommunications'.

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Notes

1. A LEO is usually less than 1000 km but can be as low as 160 km above the Earth's surface and up to 2000 km.
2. An ASAT is a form of weapon test used to destroy a satellite in the event of space warfare (due to the huge dependency of some nations on working satellites, particularly for military purposes).
3. There have, for example, been more than 170 explosions recorded in LEO (Schildknecht, 2007: 48).
4. The US Space Surveillance Network (SSN) 'is a network of sensors located at two dozen sites worldwide and operated by U.S. Army, Navy, and Air Force personnel' (Kelso, 2019).
5. Payloads and rocket bodies are parts of structures (i.e., rockets) used to launch other objects (such as satellites) into LEO.

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