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Potential negative effects of the Brazilian Space Program on coastal sharks

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The Brazilian government recently announced its first partnerships with the private sector, including American and Canadian companies, to use the Alcântara Space Center (Maranhão, northern Brazil). This center is known for its privileged location, saving up to 30% of fuel in launches. Its operationalization is an offshoot of the Technological Safeguards Agreement, which is important for the Brazilian Space Program due to greater space sector investments and environmentally relevant projects. In 2003, a major fire at the Alcântara Space Center destroyed a rocket and killed 21 workers, halting Brazilian Space Program activities. Recently, our research group reported serious environmental consequences of this accident, i.e., extremely high amounts of Rubidium (Rb) in apex predatory sharks near the Alcântara Space Center. This element is used in fuels and in space propulsion systems and is potentially toxic, displaying bioaccumulating and biomagnifying capabilities. The observed concentrations are the highest ever detected in any living organism (up to 24.65 mg kg-1 dry weight). The launch base is located on the Brazilian Amazon Coast, and population recruitment impacts may compromise biota conservation and biodiversity. Local shark meat consumption is also worrying, as consumers may be exposed to Rb, whose effects in humans are unknown. We, therefore, indicate an urgent need for biomonitoring efforts in the area, as the Alcântara Space Center is about to operate at its maximum capacity.

KEYWORDS

space race, rocket launching, environmental disaster, public policies, Brazilian Amazon Coast

The space sector has undergone major transformations worldwide in the last few years, mainly due to the ongoing privatization of space activities, aiming at space tourism and "the race to Mars", in turn mostly possible due to the availability of professionals fired by NASA, after successive cuts in public funds in the last 10 years. This trend is also observed in other countries (e.g., Russia and Kazakhstan) (Kovalev et al., 2019). In Brazil, the Brazilian Space Agency is an autonomous agency belonging to the Ministry of Science, Technology, and Innovation and is responsible for the Brazilian Space Program. This agency has ensured the country's prominence in the South American space race, making Brazil an International Space Station project partner (Gouveia, 2003). Initially, under the command of the military, the agency was transferred to civilian control in 1994 (Figure 1A). Since then, the Brazilian Space Program has pursued a policy of joint technology development with more advanced space programs, including BRICS members, Ukraine, and the United States, depending on the space race agenda of the political party in power (AEB, 2015) (Figure 1B).

The Alcântara Launch Center is the second launch base under the command of the Brazilian Air Force, located in the state of Maranhão, on Brazil's northern Atlantic coast. The Alcântara Launch Center Nucleus was activated on March 1, 1983, considered the official opening date (FAB, 2017a) (Figure 2). However, only in November 1989 did the Alcântara Launch Center become effectively operational, as many families, including

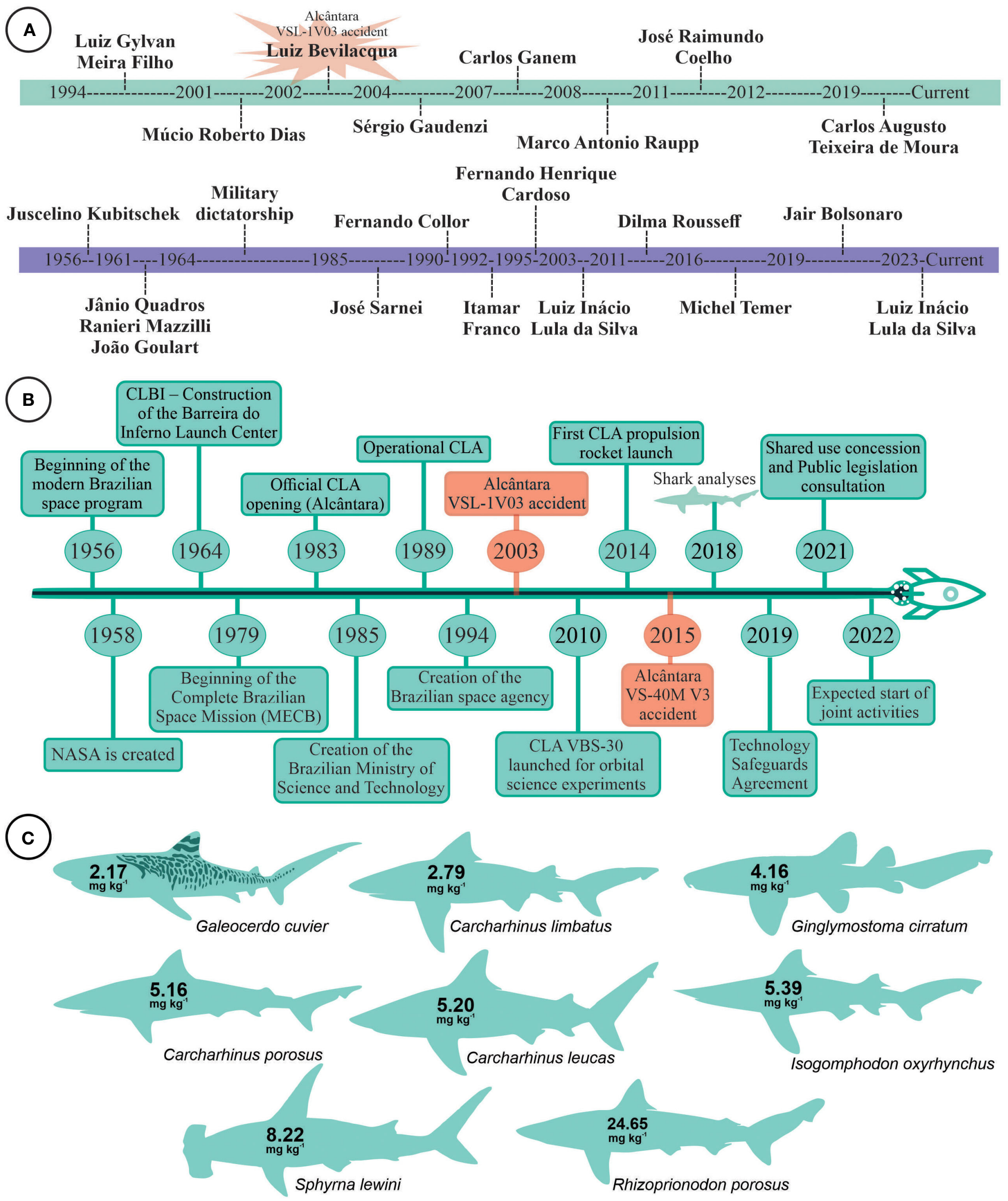

FIGURE 1
(A) Timeline of the Brazilian authorities relevant to the present study. The green band indicates the authorities responsible for the Brazilian space program, while the purple band depicts Brazilian presidents in the same period. **(B)** Timeline summarizing the Brazilian Space Program activities since its inception, along with the main events related to the national space race, including the two main disasters at the Alcântara Launch Center (orange). **(C)** Mean of Rubidium concentrations found in muscle tissue of eight shark species sampled around the Alcantara Launch Center.

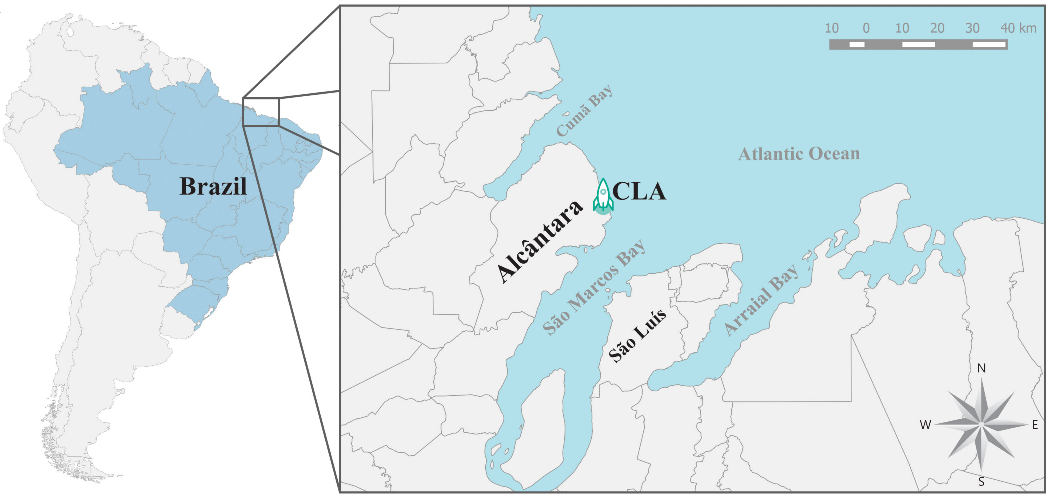

FIGURE 2
The Alcântara Launch Center, located in the state of Maranhão, on Brazil's northern Atlantic coast.

traditional "quilombolas" (direct Afro-Brazilian descendants of African slaves, residents of settlements first established by escaped slaves in Brazil), who lived on the island of Alcântara had to be relocated, an issue still not solved by the State Government. The first launch carried out at the Alcântara Launch Center was called "Mission Pioneer", and aimed to launch the first SBAT-type rocket carrying payloads for biological and physical tests (FAB, 2017b). The center was built as an alternative to the Barreira do Inferno Launch Center, located in the state of Rio Grande do Norte, as high-density urban areas did not allow for base expansions (Figure 1B). The Alcântara Launch Center is known for its privileged location, allowing for savings of up to 30% in fuel consumption used for rocket and satellite launches. Its proximity to the Equator allows for launches to any orbit and constant local weather conditions allow for launches to take place almost all year round without delay (FAB, 2017c). All of these characteristics have transformed the Alcântara Launch Center into the largest Brazilian Space Center and boosted the Brazilian space conquest. Since then, more than 44 launches have been carried out, including probes, sounding rockets, training rockets, and rocket launch vehicles (i.e., VLS). This is, however, a significant cause of concern, as these activities are known to result in high environmental contamination levels due to the employed fuel compounds, resulting in both direct and indirect environmental and human health risks (Carlsen et al., 2008). In fact, territorial integrity and national heritage concerning the effects of space race are fundamental, as Brazil is the largest country in South America and the fifth-largest in the world, being susceptible to accidents resulting from the fall of space debris on its soil (Vieira et al., 2021).

In 2003, a major fire followed by explosions at the Alcântara Launch Center led to the destruction of the Brazilian VLS-1 V03 rocket and the death of 21 civilian technicians, resulting in a major controversy and halting Brazilian Space Program activities (Figure 1B) (G1, 2016). The VLS-1 V03 was loaded with two types of fuel, a solid propellant mixed with chemical additives responsible for combustion (i.e., metal catalysts) and a liquid propellant, responsible for increasing buoyancy force and preventing the rocket from rotating around its axis. The exact composition of both propellants was not disclosed in the official report. The objective of the mission, named "Operation São Luís", was to place a SATEC meteorological microsatellite from the Brazilian National Institute for Space Research and a UNOSAT nanosatellite from the University of the North of Paraná in an equatorial circular orbit at an altitude of 750 km (Brazilian Space, 2009). The accident occurred three days before the scheduled launch date, on August 22, 2003. At the time of the accident, the president of the Brazilian Space Agency was in the midst of announcing the agreement signed between Brazil and Ukraine concerning Alcântara Launch Center use. According to the official report, the ignition process occurred ahead of schedule, so the launch tower was not removed in time, becoming the main fire cause. In 2015, another explosion occurred, during the launch of the VS-40M V3 suborbital rocket in the "Operation São Lourenço" (Figure 1B). The entire rocket was lost and the launch structure was damaged (G1, 2015). Fortunately, no deaths occurred, although this accident may have been an additional source of environmental contamination in the region.

On April 26, 2021, the Brazilian Space Agency published Public Consultation Notice No. 3, a public call to update Ordinances No. 5 (AEB, February 21, 2002) and No. 182 (AEB, May 28, 2020), both aimed at regulating Brazilian space activities. Despite representing an advance, public suggestions hardly reflect the complexity of government measures that must be adopted to prevent future accidents from causing environmental impacts, as discussed in the next sections. Furthermore, no normative or ordinances concerning potential environmental disasters due to the Brazilian space race have been implemented to date, no environmental studies are required to establish launch bases, and no regular inspections are mandated.

For example, primary pollutants that can result from space fuel burning may undergo transformation processes (i.e., secondary pollutants), displaying the potential for accumulation and biomagnification processes (Carlsen et al., 2008). In this regard, our research group has recently reported serious environmental consequences of the Alcântara Launch Center accident, in the form of extremely high amounts of Rubidium (Rb) in the vicinity of Alcântara Island (Wosnick et al., 2021). This element is used in fuels and as part of space propulsion systems and, although rarely detected in wild animals, appears to be toxic, mainly to the reproductive system (Yamaguchi et al., 2007), displaying bioaccumulating and biomagnifying capabilities throughout trophic networks (Campbell et al., 2005; Anandkumar et al., 2019). Rubidium was, in fact, detected in the muscle tissue of several other top marine predators in the vicinity of the Alcântara Launch Center following the same methodology applied in the aforementioned study (see Wosnick et al., 2021 for further details) including tiger sharks (*Galeocerdo cuvier*), bull sharks (*Carcharhinus leucas*), Atlantic nurse sharks (*Ginglymostoma cirratum*), smalltail sharks (*Carcharhinus porosus*), blacktip sharks (*Carcharhinus limbatus*), Atlantic sharpnose sharks (*Rhizoprionodon porosus*), daggernose sharks (*Isogomphodon oxyrhynchus*) and scalloped hammerhead sharks (*Sphyrna lewini*) (Figure 1C), considered promising sentinel species, as higher trophic level species are adequate environmental contamination bioindicators, reflecting the biological effects of environmental disasters (Torres et al., 2014). It is important to note the fact that no other sources of Rb exist in the state of Maranhão, and that the detected Rb concentrations are the highest ever reported in any living organism, ranging from 2.17 to 24.65 mg kg-1 dry weight (Figure 1C). This is of particular concern, as the Alcântara Launch Center is located within the Brazilian Amazon Coast, an area that boasts of great fauna richness and biological relevance. In addition, it is also a hotspot for endemic and threatened sharks and their relatives (Dulvy et al., 2014), and any impacts on population health and recruitment may irreversibly compromise local fauna conservation.

Rubidium has also been detected in Arctic sharks, albeit at much lower concentrations (Pacific sleeper shark, 0.79 mg kg-1; Greenland shark, 0.66 mg kg-1) (McMeans et al., 2007). This is interesting, as rocket stages from SS-19 intercontinental missiles re-purposed for launching satellites into the Arctic Sea were dropped by Russia in the area on ten occasions since 2002. As a result of these drops, toxic space fuel components (e.g., unsymmetrical dimethylhydrazine) have been identified in the region (Byers and Byers, 2017), potentially the source of the detected Rb in Arctic sharks. However, as the sharks were sampled before 2002, it is possible that the Rb sources originate from other activities or even from rocket stage drops performed prior to the published assessments.

Besides Rb, several other potential residual contaminants from this accident may have been discharged in the surrounding aquatic ecosystem. These include many organic compounds, such as ammonium nitrate, potassium chlorate, ammonium chlorate, hydrocarbons, kerosene, alcohol, hydrazine and its derivatives and liquid hydrogen, as well as inorganic compounds, i.e., boron, lithium, aluminum and magnesium, all a part of rocket fuel according to the National Aeronautics and Space Administration (NASA, 2023). All are toxic to aquatic biota, both invertebrates and vertebrates, in general to some degree. Hydrazine in particular, is a confirmed animal carcinogen (ACGIH, 2000) and has been reported as causing cytotoxicity and reproductive alterations in fish (Rajagopal et al., 2019). Hydrocarbons are also cyto- and genotoxic to many aquatic biota representatives, and display the ability to bioaccumulate and, in some cases, biomagnify throughout trophic food webs, depending on their chemical class (Trowbridge and Swackhamer, 2002). Metallic elements, even essential ones like B, Li and Mg, may be toxic depending on their concentration (Jaishankar et al., 2014), while Al has been noted as mostly toxic to aquatic organisms (Sparling and Lowe, 1996). Thus, further monitoring efforts in this region are warranted to evaluate potentially deleterious impacts on locally exposed biota.

Apart from a conservationist point of view, the high consumption of shark meat across the Brazilian Amazon Coast (Barbosa-Filho et al., 2019) is also a call for concern, as consumers may be exposed to high Rb concentrations, whose effects in humans are unknown. In fact, Brazil is one of the largest shark meat consumers worldwide (Bornatowski et al., 2018), and even with increasing indications of high contaminant concentrations in shark meat (Souza-Araujo et al., 2021), no sanitary surveillance programs are currently in force, and no safe consumption levels for Rb have been established. In fact, to date, most countries that rely on space launches have not established environmental disaster monitoring and prevention programs, including Brazil. Fortunately, biomonitoring methods and computational modeling methodologies are available to assess the potential effects of space fuel combustion, as well as gas behavior when released into the environment, allowing for real-time assessment of the impacts of both orbital and suborbital launches (Conn et al., 1975; Carlsen et al., 2008).

To date, the most significant sources of marine pollution through environmental disasters in Brazil consist of oil extraction/transportation activities, with many studies carried out on the affected fauna and environment (Michel, 2000; Ruoppolo et al., 2017; Craveiro et al., 2021). Both domestic and international legislation tailored to environmental disasters are, of course, required in these situations and must be coupled with government efforts to inspect public and private enterprises before accidents occur. Unfortunately, Brazil's reality hardly reflects this ideal disaster prevention model, with thousands of human and non-human lives paying the price (Brum et al., 2020). Furthermore, even with high media attention, most environmental disasters in the country, even if recurrent, remain without punishment to those involved, and usually, no robust environmental studies and compensatory measures are applied. Furthermore, environmental compensations are rarely carried out voluntarily, even less so imposed by Brazilian courts, and, when they are, the guilty parties simply do not pay up.

When accounting for the potential impacts of rocket explosions, this is even more concerning. However, as noted in other disasters in the country, the guilty parties were not held accountable in the case of the Alcântara explosion. Astonishingly, this impunity is supported by the Brazilian space legislation which sustains through decree established based on in the "Convention on International Liability for Damage Caused by Space Objects" in 1972. This document states that: "(a) the term "damage" means loss of life, personal injury or other impairment of health, beyond loss or damages of properties;" That is, any environmental impacts will not be classified as damage, making the application of appropriate measures unattainable. As a result of environmental neglect, the Alcântara Launch Center has operated without an environmental license and without an environmental impact study for about 40 years, making it impossible to identify the possible impacts generated during these years of activity (MABE, 2019).

Recently, the Brazilian Space Agency announced the second public call for private companies to use along the northeast coast, focusing on attracting companies with the capacity to carry out larger launches, in addition to exploring the nine thousand hectares of the base (Agência Brasil, 2021). The first call provided the sending of documentation from 14 companies, with nine final proposals from joint partnerships between Brazilian and foreign companies. The arrival of private companies represents a Brazilian Space Program boost, as budget restrictions have recently been applied to space operations. More specifically, in the beginning of 2021, the Brazilian Space Agency suffered a 1.2 million reais cut in its budget, which also affected the Alcântara Launch Center. On April 29th 2021, the Brazilian government announced its first partnership with foreign private companies, including Hyperion, Orion AST, Virgin Orbit (USA), and C6 Launch (Canada), to make use of the Alcântara Launch Center (TecMundo, 2021). According to the Brazilian Space Agency, each company will be responsible for operating a space center unit in Alcântara. The VLS platform system will be operated by Hyperion, the suborbital launcher, by Orion AST and the Alcântara airport will be maintained under the control of Virgin Orbit. The C6 Launch was chosen to manage the Profiler Area (Agência Brasil, 2021). Nanosatellite launches will be one of the priorities from these new agreements. This operationalization is an offshoot of the Technological Safeguards Agreement between Brazil and the United States, signed by Jair Bolsonaro and Donald Trump in 2019 (G1, 2019). This agreement is extremely important for the Brazilian Space Program, endorsing projects of significant environmental relevance, such as the Amazonia-1 satellite launched from the Indian Space Research Organization (ISRO), in February 2021 during the PSLV-C51 mission, which will monitor Amazon deforestation rates. In the agreement, the government of the United States of America ensures that North American Representatives or North American Licensees are allowed to provide the Brazilian government with information related to the presence of radioactive material or any substances defined as potentially harmful to the environment or human health. However, the Brazilian government may only carry out any study or photographic record if authorized and monitored by the Government of the United States of America, and even then, it shall take all necessary measures to avoid public disclosure of any information collected.

To date, no agreement to reallocate financial resources to monitor potential impacts of future launches has been disclosed. Furthermore, Brazilian legislation does not provide for any punitive measure for international private companies that use the Alcântara Launch Center facilities, pointing to a scenario very similar to that observed in previous agreements between the Brazilian government and multinationals involved in major environmental disasters. It is worth mentioning that the Alcântara Launch Center security area covers the entire coast of Alcântara, during the rocket launch period, the region is restricted, the community is prohibited from fishing for up to 40 days and there is no compensatory measure during this period of prohibition.

The constant advances of the space race require permanent incorporation of best practices, ensuring the safety of space activities not only in Brazil, but in all countries engaged with launch programs. In this scenario, it is clear that the Brazilian space race requires public policies to guide and monitor upcoming activities from private companies' that will make use of Alcântara Launch Center facilities, and the Brazilian government must become aware of the potential impacts that increasing space activities may cause. It is also imperative that inspections be carried out at the Alcântara Launch Center, preferably within the Brazilian Ministry of the Environment and the State Secretariat for the Environment. The agreements that are being signed should also contain specific clauses for the implementation of environmental disasters monitoring and prevention efforts, as well as guaranteed funds in case of new disasters. Lastly, it is paramount that the domestic legislation on space activities be revised, relying not only on public and specialists in space activities, but also environmental specialists to provide scientific consultancy and to direct mitigation measures, if necessary.

Considering the reported impacts, it is also paramount that compensation measures be adopted, directing public resources to neutralize the effects of chemical compounds released in the vicinity of Alcântara. Furthermore, from a public health perspective, initiatives concerning the monitoring of fish quality (particularly shark meat, as regional characteristics make this one of the most consumed meats in the Alcântara Launch Center region) should be implemented, preferably comprising joint activities between both State Fisheries and Health Departments.

The environmental risks of space exploitation to Earth's environment has been highlighted recently by Napper et al. 2023. The authors suggest that there needs to be a global treaty focussing on Earth's orbit, with the agreement including measures to implement producer and user responsibility for satellites and debris, from the time they launch, through-life impacts on the night-sky and at the end of life. It was also stated that enforcement of collective international legislation should be put in place, including fines and other incentives to ensure accountability. Finally, the treaty should require that any countries with plans to use Earth's orbit commit to global cooperation. That being said, it is important to ensure any impacts to the biodiversity on Earth will also be included in such a treaty.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

Conceptualization: NW and RH-D. Data curation: NW, AC, JN, and RH-D. Funding: JN. Visual content: RD and AC. Writing - original draft: NW, AC, RD, and RH-D; Writing - review & editing: NW, JN, and RH-D. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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