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Environmental degradation, climate extremes, and cancer risk in the Amazon: a Planetary Health perspective

Degradação ambiental, extremos climáticos e risco de câncer na Amazônia: uma perspectiva de Saúde Planetária

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ABSTRACT

The Amazon rainforest, a critical regulator of global ecological balance, is undergoing environmental changes that may indirectly influence human health outcomes, including potential impacts on cancer risk. This review explores how climate change and pollution influence cancer rates, using epidemiological studies, ecological monitoring, and health data within a Planetary Health framework, emphasizing the interconnection between human health and ecosystems. Environmental damage in the Amazon increases cancer risks through several pathways. Forest fires emit carcinogens, elevating respiratory and neurological cancers. Deforestation boosts UV exposure, raising skin cancer risks, especially for outdoor workers. Heavy metal pollution, chiefly mercury from illegal gold mining, bioaccumulates in the food chain, heightening carcinogenic risks, with climate-induced floods worsening toxicity. Additionally, extreme weather events disrupt cancer treatment infrastructure, reducing access to care in remote areas. Vulnerable groups such as Indigenous peoples, river communities, and Afro-descendants bear the brunt of these risks, with carcinogen buildup and limited healthcare access intensifying health disparities. Addressing this crisis requires integrated strategies grounded in environmental justice and Planetary Health principles, along with policies to protect ecological and human health. The Amazonian context serves as a stark warning for other tropical regions under similar pressures, highlighting the urgency of climate action as an essential component of cancer prevention.

Keywords: Amazon; Climate Change; Environmental Justice; Indigenous Health; Health Equity; Cancer.

RESUMO

A Floresta Amazônica, um regulador crucial do equilíbrio ecológico global, vem passando por mudanças ambientais que podem influenciar indiretamente os desfechos de saúde humana, incluindo possíveis impactos sobre o risco de câncer. Esta revisão explora como as mudanças climáticas e a poluição influenciam as taxas de câncer, utilizando estudos epidemiológicos, monitoramento ecológico e dados de saúde dentro do referencial da Saúde Planetária, enfatizando a interconexão entre a saúde humana e os ecossistemas. Os danos ambientais na Amazônia aumentam os riscos de câncer por diversos mecanismos. Incêndios florestais emitem substâncias carcinogênicas, elevando a incidência de cânceres respiratórios e neurológicos. O desmatamento intensifica a exposição à radiação ultravioleta, ampliando o risco de câncer de pele, especialmente entre trabalhadores ao ar livre. A poluição por metais pesados — principalmente mercúrio proveniente do garimpo ilegal — bioacumula-se na cadeia alimentar, elevando o risco carcinogênico, enquanto as inundações induzidas pelo clima agravam a toxicidade. Além disso, eventos climáticos extremos prejudicam a infraestrutura de tratamento do câncer, reduzindo o acesso à assistência em áreas remotas. Grupos vulneráveis, como povos indígenas, comunidades ribeirinhas e afrodescendentes, sofrem de forma desproporcional esses impactos, uma vez que o acúmulo de carcinógenos e o acesso limitado à assistência à saúde ampliam as desigualdades. Enfrentar essa crise requer estratégias integradas baseadas na justiça ambiental e nos princípios da Saúde Planetária, juntamente com políticas que protejam a saúde ecológica e humana. O cenário na Amazônia serve como um alerta contundente para outras regiões tropicais sob pressões semelhantes, destacando a urgência da ação climática como componente essencial da prevenção do câncer.

Palavras-chave: Amazônia; Mudança Climática; Justiça Ambiental; Saúde Indígena; Equidade em Saúde; Câncer.

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INTRODUCTION

The Amazon, the largest tropical rainforest on the planet, has long been recognized for its vital role in regulating climate, preserving biodiversity, and maintaining hydrological cycles. However, this ecosystem, once regarded as a natural bastion of planetary stability, is now at the epicenter of profound environmental transformation, driven by large-scale deforestation, recurrent fires, expanding mining operations, and agricultural activities[1,2]. The urgency of this situation suggests that the environmental degradation of the Amazon could have major consequences, potentially affecting human health. Although it is difficult to establish direct causation, there are growing concerns that such degradation might contribute to issues such as an increased incidence of cancer among local populations[3].

This review is based on the premise that the Amazon is becoming a "sentinel ecosystem", where rapid and visible interactions between environmental change and health outcomes may predict patterns likely to occur in other tropical regions under similar pressures. The area represents an emblematic case of how simultaneous exposure to multiple carcinogenic agents, such as the inhalation of smoke[4], consumption of water contaminated with heavy metals[5], ingestion of toxic foods[6-8], and exposure to intensified solar radiation due to forest loss creates a chronic, complex, and underestimated oncological risk environment. This scenario is not merely a collection of isolated risks; rather, it exhibits a compounding effect, as overlapping contamination pathways and recurrent extreme events contribute to an exceptionally high and persistent cancer risk, underscoring the interconnectedness and complexity of the problem.

At the same time, the fragility of regional health infrastructure, combined with challenging geography and inadequate public policies tailored to local realities, severely undermines oncological response capacity[9]. The convergence of ecological, health, logistical, and social vulnerabilities makes the Amazon a striking expression of health inequities. In this context, it is essential to adopt a health equity perspective, which entails recognizing and addressing systemic disparities in health outcomes that are often rooted in social and economic inequalities. This approach acknowledges that the most affected groups — Indigenous peoples, riverine communities, Afro-descendant rural populations (*quilombolas*), and rural workers — are historically marginalized and currently face the greatest exposure burden and the least access to protection and cancer treatment.

This review proposes that a comprehensive and transdisciplinary approach is crucial to exploring potential links among climate, environment, and cancer in the Amazon region. It recognizes that health and environmental issues are interconnected and that an emerging framework such as Planetary Health may provide valuable insights into this complex relationship. By integrating scientific evidence, ethical considerations, and philosophical reflection, the aim is to identify key challenges and outline pathways toward public policies for cancer prevention that are more equitable, preventive, and sustainable.

MATERIALS AND METHODS

STUDY DESIGN AND SCOPE

This narrative review incorporates integrative elements to map and interprets potential links between environmental degradation, climate variability, and cancer in the Amazon. The approach privileges breadth and triangulation across epidemiology, exposure science, molecular mechanisms, health systems, and ethical–social analyses. The synthesis is qualitative; no meta-analysis was conducted.

CONCEPTUAL FRAMEWORK

Selection, appraisal, and synthesis were guided by the Planetary Health and Environmental Justice frameworks. Evidence was organized along exposure–pathway–outcome axes relevant to the Amazon: inhaled toxicants from biomass burning, solar ultraviolet (UV) exposure, heavy metals and other contaminants in water and food webs, and climate-related disruptions to oncological care.

INFORMATION SOURCES AND SEARCH STRATEGY

We searched PubMed/MEDLINE, Scopus, Web of Science, SciELO, and LILACS, complemented by targeted Google Scholar queries and backward/forward citation tracking from key papers already known to the authors. The search prioritized studies published mostly from March 2014 to March 2025, encompassing the most recent decade of research. Search strings combined controlled vocabulary and free text in English, Portuguese, and Spanish, including terms such as *Amazon/Amazônia/Amazonas*, *climate change*, *wildfire smoke*, *$PM_{2.5}$*, *PAH*, *mercury/methylmercury*, *artisanal gold mining*, *ultraviolet radiation*, *cancer*, *Indigenous health*, *environmental justice*, *health-system resilience*, *cancer incidence/mortality*, *biomarkers*, and *exposure assessment*.

ELIGIBILITY CRITERIA

Inclusion: peer-reviewed studies and authoritative reports addressing Amazonian populations or ecosystems and at least one of the following: carcinogenic exposures pertinent to the region; cancer outcomes (incidence, mortality, staging, survival); mechanistic endpoints plausibly linked to carcinogenesis with contextual applicability; or health-system impacts of climate extremes relevant to cancer care. Eligible study designs included cohort, case–control, time-series, and cross-sectional epidemiological studies, as well as environmental exposure assessments, experimental/mechanistic investigations, and health-systems or implementation research.

Exclusion: studies outside the Amazon without transferable mechanisms; purely ecological papers

lacking a health or exposure link; non–peer-reviewed opinion pieces; and animal or *in vitro* studies with limited generalizability to Amazonian conditions.

SCREENING, DATA EXTRACTION, AND SYNTHESIS

Titles and abstracts were screened for relevance, and full texts were reviewed when appropriate. Reference lists of included studies were also examined to identify additional region-specific evidence. The studies were analyzed with attention to their design, context, population, exposures, outcomes, and limitations. Their main contributions were integrated thematically across four domains: air pollution and wildfires; UV radiation and cancer; heavy metals and food-web contamination; and climate extremes affecting cancer care and equity.

CLIMATIC AND ENVIRONMENTAL FACTORS IN MODULATING CANCER RISK IN THE AMAZON

AIR POLLUTION AND FOREST FIRES: INHALED CARCINOGENS AND THEIR ONCOLOGICAL IMPACT

Forest fires in the Amazon, exacerbated by climate change and human activities such as deforestation, are a major source of atmospheric pollution. The smoke produced by these fires is a complex mixture of substances that includes known human carcinogens such as particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), and various volatile organic compounds (VOCs)[2]. Smoke from fires in the Amazon can be extremely toxic, reflecting the severity of air-quality degradation[10]. Researchers have confirmed that wildfire smoke can induce cancer, with studies demonstrating how this smoke causes genetic damage and leads to human lung-cell death, revealing a direct biological mechanism for carcinogenesis[11].

Exposure to pollutants from wildfires has been linked to an increased risk of respiratory cancers, including lung cancer, and there is some evidence suggesting associations with other malignancies such as brain tumors. A long-term study conducted by McGill University observed that individuals residing within a 50 km radius of wildfires had a higher incidence of brain tumors (10%) and lung cancer (4.9%), indicating a potential correlation between proximity to wildfires and cancer risk. Chronic exposure is a concern, as wildfires recur annually in some areas, potentially leading to repeated exposure to carcinogenic pollutants. Research on wildland firefighters also suggests they may have an increased risk of lung cancer, with estimates ranging from 8% to 43%. While these findings raise important public-health considerations, more research is needed to establish definitive causal relationships between wildfire exposure and cancer[12]. Furthermore, exposure to wildfires has been associated with poorer survival outcomes in patients recovering from lung-cancer surgery, underscoring the increased vulnerability of individuals with preexisting conditions[13]. Researchers emphasize that wildfires often recur in the same regions each year, meaning that nearby communities may face ongoing exposure to PMs[14-17].

The annual recurrence of forest fires results in chronic exposure to a persistent burden of carcinogens for nearby populations, with health risks extending far beyond the active burning period. After the fires are extinguished, pollutants such as heavy metals and PAHs remain in the environment, contaminating air, soil, and water through deposition and runoff, and persisting for extended periods[18]. Chronic exposure to these substances causes cumulative DNA damage and impairs cellular repair mechanisms, which are critical drivers of cancer development[19]. Studies have shown that the health risks associated with such chronic, low-level exposure are often underestimated compared with those of acute events. Nonetheless, they contribute to long-term increases in respiratory and other cancers, as well as cardiovascular disease[12].

The toxicity of wildfire smoke is not merely the sum of its pollutants; rather, the complex mixture — including $PM_{2.5}$, PAHs, VOCs, and heavy metals — can interact synergistically, amplifying overall toxic and carcinogenic effects[20,21]. This complexity makes it difficult to isolate single causative agents, necessitating a holistic risk-assessment approach. Moreover, vulnerable groups such as children, older adults, and individuals with preexisting respiratory conditions are disproportionately affected by air pollution[11,19]. Consequently, the carcinogenic impact of these complex smoke mixtures is heightened in populations already facing health disparities or environmental stressors, resulting in a higher effective cancer risk due to both the nature of the exposure and the susceptibility of the affected population.

UV RADIATION: SUN EXPOSURE AND SKIN CANCER PREVALENCE

The Amazon's location near the Equator naturally exposes it to high levels of UV radiation, and recent research confirms that UV irradiance in the region is both intense and subject to seasonal peaks, especially during the dry season and around solar noon[22]. This intrinsic geographic factor, combined with growing human-induced environmental changes such as extensive deforestation, significantly increases direct population exposure to UV radiation. Occupational and environmental exposure to solar UV, particularly in equatorial regions like the Amazon, further elevates this risk, and global analyses estimate that nearly one-third of non-melanoma skin cancer deaths and disability-adjusted life years are attributable to UV exposure, especially among outdoor workers and older adults[23].

A short clinical–epidemiological study conducted in Manaus (Amazonas) between 2008 and 2018 with 543 patients confirmed that basal cell carcinoma was the most common type of skin cancer, accounting for 75.5% of cases, followed by squamous cell carcinoma at 18.1%. Most tumors (71.3%) were located on the head and neck, areas most exposed to sunlight, highlighting the strong association between UV radiation and skin-cancer incidence. Street cleaners, street vendors, and rural workers such as those in agriculture and fishing were identified as particularly vulnerable due to prolonged occupational exposure

to sunlight. These findings reinforce the critical role of cumulative UV exposure in the development of non-melanoma skin cancers and underscore the need for targeted prevention strategies, particularly for high-risk occupational groups[24].

Although the Manaus study did not establish a definitive causal link between deforestation and increased UV exposure, it suggests a potential association that warrants attention. The observation that reduced forest cover diminishes natural shade indicates that individuals living and working in deforested areas, especially those spending considerable time outdoors, may experience more direct sunlight exposure. However, these findings should be interpreted cautiously, as multiple factors can influence UV exposure and skin-cancer risk. This example illustrates how environmental change driven by human activity could exacerbate natural risks, such as skin cancer in the Amazon, while emphasizing the need for further research to confirm these associations. It highlights the complex and interdependent pathways through which climate and environmental changes may impact health, underscoring the importance of cautious interpretation of current evidence.

HEAVY METALS AND CARCINOGENIC RISK: MERCURY, ARSENIC, AND THE FOOD WEB IN THE AMAZON

The Amazon is severely affected by heavy-metal contamination, primarily driven by illegal gold mining[25]. This activity frequently employs mercury (Hg) for amalgamation, resulting in widespread pollution of aquatic environments. Consequently, fish populations — and, critically, human consumers, particularly Indigenous communities — are heavily impacted[26,27].

Beyond Hg, other non-essential and highly toxic metals such as arsenic (As), cadmium (Cd), and lead (Pb), originating from industrial waste, domestic sewage, and agricultural fertilizers, also pose significant carcinogenic risks[28]. These metals accumulate in ecosystems and human tissues, potentially leading to various cancers years after exposure[29]. Cadmium exposure, particularly in occupational settings or through contaminated food and water, is associated with lung, breast, and prostate cancers, and can also cause kidney damage and other systemic effects[28,30]. The mechanisms underlying these risks include oxidative stress, DNA damage, impaired DNA repair, and genomic instability, which together drive the carcinogenic potential of these metals.

A study in the Cassiporé River basin, Amapá State, confirmed widespread contamination, reporting levels of chromium (Cr) and Hg exceeding safety thresholds in several fish species, as well as elevated concentrations of Cd, Cr, copper (Cu), Pb, and Hg in water samples. These concentrations represent a substantial health hazard to riverine populations that consume both contaminated water and fish[31].

Carcinogenic risk may be amplified through trophic transfer and bioaccumulation within Amazonian food webs. The Cassiporé study suggested that carnivorous fish exhibited higher concentrations of Cd, Cu, Pb, and Hg, indicating a potential pattern of biomagnification. This finding implies that the risk is not limited to environmental presence but extends through the food web, potentially leading to higher toxin levels in organisms central to local diets, especially fish. Such accumulation may pose health concerns for human populations connected to these aquatic ecosystems, although further research is needed to clarify the long-term implications. The association between gold mining and fish contamination highlights an exposure pathway that warrants careful investigation[31].

Flooding plays a critical role in exacerbating carcinogenic pathways by promoting the microbial conversion of inorganic Hg, often released by mining, into methylmercury (CH_3Hg^+), a far more toxic and bioaccumulative form. The Cassiporé River study indicates that flood events, which are expected to become more frequent and intense due to climate change, significantly influence Hg and Cd concentrations in fish, thereby increasing health risks for local populations. In flooded wetlands, anoxic (oxygen-depleted) conditions and abundant organic matter create ideal environments for mercury-methylating bacteria, which rapidly transform inorganic Hg into CH_3Hg^+[32]. This process leads to elevated CH_3Hg^+ levels in aquatic organisms, which then biomagnify up the food web, posing substantial neurotoxic and carcinogenic risks to humans who consume contaminated fish[33,34]. Research from various wetland and reservoir systems confirms that flooding, whether from natural events or human activities such as dam construction, can cause sharp increases in CH_3Hg^+ production and bioaccumulation, with effects that persist for years[34,35].

These findings suggest a potential link between environmental changes, such as increased flooding possibly related to climate change, and public health, especially in regions affected by heavy-metal contamination. While climate change may contribute to environmental stressors and affect the bioavailability and toxicity of existing carcinogens such as Hg, further research is required to establish a definitive connection between these factors. This potential interaction could increase health risks in the Amazonian environment; however, conclusions should be drawn cautiously until more evidence becomes available.

EXTREME WEATHER EVENTS AND THE CHALLENGES OF ONCOLOGICAL CARE IN THE AMAZON

IMPACT OF FLOODS AND DROUGHTS ON HEALTH INFRASTRUCTURE AND ACCESS TO CANCER SERVICES

Extreme climate events in the Amazon, such as severe floods and prolonged droughts, are increasingly disrupting an already fragile health infrastructure, making it difficult for communities to access essential healthcare services, including cancer care that relies on timely and continuous treatment[36]. These events can render roads impassable, interrupt river transport,

the primary means of travel in many remote areas, and damage or isolate medical facilities, further limiting healthcare delivery. The compounded effects of climate change and environmental degradation intensify these challenges, as health systems are often under-resourced and ill-prepared for the scale and frequency of such disruptions[37]. Indigenous and local communities have developed adaptive strategies, such as utilizing traditional knowledge and resource-sharing networks; however, official health responses often tend to be reactive and insufficient for achieving sustained resilience.

Cancer treatment is a complex, multi-phase process that typically involves access to diagnostics, surgery, chemotherapy, radiotherapy, and long-term follow-up. Floods may hinder patients' ability to reach healthcare facilities, and fluctuating river levels, combined with remote locations, can pose challenges for pharmaceutical logistics. These extreme weather events have the potential to disrupt the continuity of care, possibly leading to missed diagnoses, treatment delays, and issues with medication supply chains. Such disruptions could, in turn, influence health outcomes, potentially leading to more late-stage presentations and higher mortality rates. Strengthening climate resilience in Amazonian health systems might benefit from integrating Indigenous knowledge, improving infrastructure, training healthcare workers, and investing in emergency preparedness, though the extent of impact remains an area for further investigation[38]. Without such measures, the growing frequency of extreme climate events will continue to undermine healthcare access and exacerbate health inequities, particularly for time-sensitive conditions like cancer[36-38].

VULNERABILITY OF INDIGENOUS AND TRADITIONAL POPULATIONS IN CANCER PREVENTION AND TREATMENT

Indigenous and traditional populations in the Amazon face profound vulnerabilities in cancer prevention and treatment due to a convergence of environmental, social, and systemic barriers. These communities experience higher rates of certain cancers, especially cervical cancer among women, who show a three- to fourfold increase in high-grade lesions and poorer access to screening and treatment compared to non-Indigenous women[39-40]. Barriers include vast geographical distances, language and cultural differences, mistrust of health services, and a lack of culturally tailored care, which lead to delayed diagnoses and fragmented treatment[39,41,42]. Even with specialized protocols, persistent challenges such as communication gaps and unprepared health professionals limit the effectiveness of interventions.

Environmental injustices, including exposure to carcinogens from contaminated water, air, and food, further elevate cancer risk, while climate-related disruptions can severely limit access to already scarce healthcare resources[40,43]. Community-based, intercultural strategies, such as involving Indigenous leaders, using native languages, and ensuring female healthcare providers, have shown promise in improving screening uptake and trust[41,42,44]. Genetic studies also highlight unique cancer susceptibility profiles among Amazonian Indigenous peoples, underscoring the need for precision medicine and early diagnosis tailored to these populations[45,46].

Overall, the cycle of environmental degradation, social inequality, and health-system inadequacy perpetuates unequal cancer outcomes, demanding integrated, culturally sensitive, and community-driven solutions.

PHILOSOPHICAL AND ETHICAL DIMENSIONS OF THE CLIMATE–HEALTH–CANCER NEXUS

REDEFINING HEALTH: THE INTRINSIC LINK BETWEEN HUMAN WELL-BEING AND ENVIRONMENTAL INTEGRITY (PLANETARY HEALTH)

The profound and undeniable connections between climate, environment, and cancer in the Amazon fundamentally challenge traditional, often anthropocentric, conceptions of health, those that separate human well-being from the health of the natural world. It becomes imperative to adopt a holistic Planetary Health perspective, which explicitly recognizes that human health and civilization depend on the flourishing of Earth's natural systems[37,47].

A shift toward a Planetary Health perspective requires public health strategies to move beyond treating individual diseases and instead address the broader ecological determinants of health, factors rooted in the environment, society–nature relationships, technology, and material living conditions[48-50]. Research highlights that human health is fundamentally dependent on the integrity of natural systems — clean air, water, food, and stable ecosystems — and that disruptions such as pollution, ecosystem degradation, and climate change directly increase disease risk and health inequities[48-50].

This approach aligns with bioethical frameworks that view health as a unity of body, spirit, and environment, emphasizing that well-being is shaped by both social and ecological contexts[48,49]. Despite longstanding recognition of these links, mainstream public health has often neglected ecological determinants, focusing instead on social or individual factors[49,51]. However, evidence shows that improvements in environmental quality, socioeconomic conditions, and sustainable practices can significantly reduce disease burden and improve population health[48,50,52]. Integrating ecological determinants into health policy means considering the impacts of environmental change, resource use, and ecosystem services on health outcomes, and promoting sustainability as a core health practice[48,53,54].

This holistic view is particularly relevant in regions like the Amazon, where environmental and social systems are deeply intertwined and health depends on the resilience of both people and ecosystems. In the Amazon, where Indigenous and traditional populations are deeply connected to rivers, forests, and local ecosystems, this interdependence is especially significant. Potential carcinogenic risks from wildfire smoke, mercury-contaminated fish, and disruptions to

cancer care due to extreme weather events illustrate how environmental deterioration can directly affect health. The Amazon could serve as a valuable example of Planetary Health, underscoring the importance of incorporating ecological well-being into public health policy and practice.

ENVIRONMENTAL JUSTICE AND THE UNEQUAL DISTRIBUTION OF RISKS: THE DISPROPORTIONATE BURDEN ON MARGINALIZED AMAZONIAN COMMUNITIES

The distribution of climate- and environment-related cancer risks in the Amazon is profoundly unequal, reflecting deep-rooted environmental injustices. Marginalized communities, particularly Indigenous peoples, riverine populations, and Afro-Brazilian rural groups (*quilombolas*), bear a disproportionate share of the negative impacts due to historical, socioeconomic, and political vulnerabilities[4,55]. Large-scale economic projects, often implemented without proper consultation or benefit-sharing, exacerbate these disparities by increasing exposure to carcinogens while simultaneously restricting access to healthcare.

Indigenous women in the Amazon experience heightened vulnerability to cervical cancer due to intersecting barriers such as geographic isolation, language differences, cultural misunderstandings, and inadequate healthcare infrastructure. These barriers are compounded by broader patterns of environmental racism and social inequality, which systematically expose marginalized populations to greater ecological hazards and health risks[56,57]. Structural racism and policy omissions, show that a disproportionate number of people living in extreme poverty reside in environmentally hazardous areas[58], while Black-Brown-Indigenous individuals are overrepresented among those affected by climate extremes, as high-temperature exposure[59].

Environmental racism in the Amazon is perpetuated by development models that prioritize resource extraction and economic gain over the health and rights of local populations, leading to persistent disparities in disease incidence, including cancer[56-58]. These inequities are reinforced by inadequate public health services, long travel distances to care, and the absence of culturally appropriate interventions, all of which disproportionately affect Indigenous women and other vulnerable groups[57].

Addressing these disparities requires not only improved access to healthcare and culturally sensitive services but also structural changes that confront environmental racism and ensure fair treatment and meaningful participation of all affected communities in policy decisions[56-58].

Evidence indicates that systemic factors in the Amazon, such as legislative setbacks, extractive economic models, and infrastructural neglect, contribute to ongoing challenges including displacement of local populations, environmental degradation, and limited access to healthcare. These injustices are closely linked to health disparities, including rising cancer rates and difficulties in obtaining timely, effective treatment. The lack of basic sanitation and barriers to cancer screening and therapy illustrate how social and environmental determinants interact, potentially amplifying public health inequities.

LEGACY FOR FUTURE GENERATIONS IN THE AMAZON

The connection between climate, environment, and cancer in the Amazon represents an emerging public health concern that demands an integrated perspective. The region exemplifies how climate-driven environmental degradation intensifies exposure to carcinogens and strains cancer care systems. Wildfires and smoke impose a chronic burden of inhaled toxicants with genotoxic potential; high background UV radiation, intensified by deforestation, may increase cancer risk; and contamination of water and food by heavy metals, particularly mercury from illegal gold mining, as well as pesticides introduces additional hazards, with flooding events further enhancing methylmercury formation.

Climate extremes also erode health system capacity by restricting access to hospitals, disrupting logistics, and compromising the continuity of therapy. These impacts disproportionately affect Indigenous and traditional communities, perpetuating inequities in prevention and treatment. Therefore, the legacy for future generations will depend on decisions made today: without substantial changes in development models and climate policy, the regional cancer burden may show unfavorable trends.

Future research should prioritize longitudinal cohorts, integrated exposure assessments, and co-designed studies involving affected communities and local stakeholders. These efforts must align with the principles of Environmental Justice, the Precautionary Principle, and Planetary Health. Only through integrated, evidence-informed, and ethically grounded approaches can we aim to safeguard health, dignity, and resilience in cancer prevention for the Amazon and beyond.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to this work.

AUTHOR'S CONTRIBUTIONS

R.M.S.M. conceived the study, performed data analysis, and wrote the first draft of the manuscript. J.M.C.S. and B.C.M.K. assisted in critical review of the text. P.P.A. supervised the study and contributed to the final revision of the manuscript.

REFERENCES

1 Albert JS, Carnaval AC, Flantua SGA, Lohmann LG, Ribas CC, Riff D, et al. Human impacts outpace natural processes in the Amazon. Science. 2023 Jan;379(6630):eabo5003.

2 Lapola DM, Pinho P, Barlow J, Aragão LEOC, Berenguer E, Carmenta R, et al. The drivers and impacts of Amazon forest degradation. Science. 2023 Jan;379(6630):eabp8622.

3 Castro MC, Baeza A, Codeço CT, Cucunubá ZM, Dal'Asta AP, De Leo GA, et al. Development, environmental degradation, and disease spread in the brazilian Amazon. PLoS Biol. 2019 Nov;17(11):e3000526

4 Galvão MFO, Alves NO , Ferreira PA, Caumo S, Vasconcellos PC, Artaxo P, et al. Biomass burning particles in the brazilian Amazon region: mutagenic effects of nitro and oxy-PAHs and assessment of health risks. Environ Pollut. 2018 Feb;233:960-70.

5 Barraza F, Maurice L, Uzu G, Becerra S, López F, Ochoa-Herrera V, et al. Distribution, contents and health risk assessment of metal(loid)s in small-scale farms in the Ecuadorian Amazon: An insight into impacts of oil activities. Sci Total Environ. 2018 May;622-623:106-20

6 González N, Souza MCO, Cezarette GN, Rocha BA, Devoz PP, Santos LC, et al. Evaluation of exposure to multiple organic pollutants in riparian communities of the brazilian Amazon: screening levels and potential health risks. Sci Total Environ. 2024 Jan;908:168294.

7 Pacheco AM, Scussel VM. Selenium and aflatoxin levels in raw Brazil nuts from the Amazon basin. J Agric Food Chem. 2007 Dec;55(26):11087-92.

8 Souza-Araujo J, Hussey NE, Hauser-Davis RA, Rosa AH, Lima MO, Giarrizzo T. Human risk assessment of toxic elements (As, Cd, Hg, Pb) in marine fish from the Amazon. Chemosphere. 2022 Aug;301:134575.

9 Garnelo L, Parente RCP, Puchiarelli MLR, Correia PC, Torres MV, Herkrath FJ. Barriers to access and organization of primary health care services for rural riverside populations in the Amazon. Int J Equity Health. 2020 Jul;19:54.

10 Yu P, Xu R, Li S, Yue X, Chen G, Ye T, et al. Exposure to wildfire-related $PM_{2.5}$ and site-specific cancer mortality in Brazil from 2010 to 2016: a retrospective study. PLoS Med. 2022 Sep;19(9):e1004103.

11 Gao Y, Huang W, Xu Z, Xu R, Gasevic D, Liu Y, et al. Wildfire-related $PM_{2.5}$ and cause-specific cancer mortality. Ecotoxicol Environ Saf. 2024 Oct;285:117023.

12 Navarro KM, Kleinman MT, Mackay CE, Reinhardt TE, Balmes JR, Broyles GA, et al. Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. Environ Res. 2019 Jun;173:462-8

13 Zhang D, Xi Y, Boffa DJ, Liu Y, Nogueira LM. Association of wildfire exposure while recovering from lung cancer surgery with overall survival. JAMA Oncol. 2023 Jul;9(9):1214-20.

14 Butt EW, Conibear L, Knote C, Spracklen DV. Large air quality and public health impacts due to Amazonian deforestation fires in 2019. Geohealth. 2021 Jul;5(7):e2021GH000429.

15 Cobelo I, Castelhano FJ, Borge R, Roig HL, Adams M, Amini H, et al. The impact of wildfires on air pollution and health across land use categories in Brazil over a 16-year period. Environ Res. 2023 May;224:115522.

16 Moura FR, Machado PDW, Ramires PF, Tavella RA, Carvalho H, Silva Jr FMR. In the line of fire: analyzing burning impacts on air pollution and air quality in an amazonian city, Brazil. Atmos Pollut Res. 2024 Apr;15(4):102033.

17 Rocha R, Sant'Anna AA. Winds of fire and smoke: air pollution and health in the brazilian Amazon. World Dev. 2022 Mar;151:105722.

18 Rao JN, Parsai T. Trends and patterns of polycyclic aromatic hydrocarbons (PAHs) in forest fire-affected soils and water mediums with implications on human health risk assessment. Sci Total Environ. 2023 Dec;905:166682.

19 Grant E, Runkle JD. Long-term health effects of wildfire exposure: a scoping review. J Clim Chang Health. 2022 May;6:100110.

20 Hwang J, Chong NS, Zhang M, Agnew RJ, Xu C, Li Z, et al. Face-to-face with scorching wildfire: potential toxicant exposure and the health risks of smoke for wildland firefighters at the wildland-urban interface. Lancet Reg Health Am. 2023 Mar;21:100482.

21 O'Dell K, Hornbrook RS, Permar W, Levin EJT, Garofalo LA, Apel EC, et al. Hazardous air pollutants in fresh and aged Western US wildfire smoke and implications for long-term exposure. Environ Sci Technol. 2020 Aug;54(19):11838-47.

22 Alves PV, Bourscheidt V, Santos LOF, Melo PRH. Seasonal variations and trends in solar UV spectral irradiances based on data from the Ozone Monitoring Instrument at solar noon in southern Amazonas, Brazil. Remote Sens Appl. 2025 Jan;37:101423.

23 Pega F, Momen NC, Streicher KN, Leon-Roux M, Neupane S, Schubauer-Berigan MK, et al. Global, regional and national burdens of non-melanoma skin cancer attributable to occupational exposure to solar ultraviolet radiation for 183 countries, 2000–2019: a systematic analysis from the WHO/ILO joint estimates of the work-related burden of disease and injury. Environ Int. 2023 Nov;181:108226.

24 Araújo AEG. Perfil clínico-epidemiológico de pacientes com câncer de pele atendidos em um centro de referência em dermatologia de Manaus [dissertação]. Manaus (AM): Universidade do Estado do Amazonas; 2020.

25 Teixeira RA, Pereira WVS, Souza ES, Jr Ramos S, Dias YN, Lima MW, et al. Artisanal gold mining in the eastern Amazon: environmental and human health risks of mercury from different mining methods. Chemosphere. 2021 Dec;284:131220.

26 Pfeiffer WC, Lacerda LD, Salomons W, Malm O. Environmental fate of mercury from gold mining in the brazilian Amazon. Environ Rev. 1993 Jan;1(1):26-37.

27 Castilhos Z, Rodrigues-Filho S, Cesar R, Rodrigues AP, Villas-Bôas R, Jesus I, et al. Human exposure and risk assessment associated with mercury contamination in artisanal gold mining areas in the brazilian Amazon. Environ Sci Pollut Res. 2015 Mar;22:11255-64.

28 Balali-Mood M, Naseri K, Tahergorabi Z, Khazdair MR, Sadeghi M. Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. Front Pharmacol. 2021 Apr;12:643972.

29 Hui X, Li A, Chang S, Wang A, Wang L, Li C. Concentrations and human health risks attributed to potentially toxic elements (PTEs) in water resources in China: systematic review and meta-analysis. Ecotoxicol Environ Saf. 2025 Feb;291:117801.

30 Zumel A, Alguacil J, Costas L, García E, Santibáñez M, Aragonés N, et al. P056 Occupational exposure to metals and risk of breast, chronic lymphocytic leukaemia, colorectal, prostate, and stomach cancer in the MCC-spain case control study. Cancer. 2016;73(Suppl 1):A139-40.

31 Lima DP, Santos C, Silva RS, Yoshioka ETO, Bezerra RM. Contaminação por metais pesados em peixes e água da bacia do rio Cassiporé, Estado do Amapá, Brasil. Acta Amaz. 2015 out-dez;45(4):405-14.

32 Windham-Myers L, Fleck JA, Ackerman JT, Marvin-DiPasquale M, Stricker CA, Heim WA, et al. Mercury cycling in agricultural and managed wetlands: a synthesis of methylmercury production, hydrologic export, and bioaccumulation from an integrated field study. Sci Total Environ. 2014 Jun;484:221-31.

33 Schartup AT, Balcom PH, Soerensen AL, Gosnell KJ, Calder RSD, Mason RP, et al. Freshwater discharges drive high levels of methylmercury in Arctic marine biota. Proc Natl Acad Sci USA. 2015 Sep;112(38):11789-94.

34 Calder RSD, Schartup AT, Li M, Valberg AP, Balcom PH, Sunderland EM. Future impacts of hydroelectric power development on methylmercury exposures of canadian indigenous communities. Environ Sci Technol. 2016 Nov;50(23):13115-22.

35 Gerrard PM, St Louis VL. The effects of experimental reservoir creation on the bioaccumulation of methylmercury and reproductive success of tree swallows (*Tachycineta bicolor*). Environ Sci Technol. 2001 Mar;35(7):1329-38.

36 Brondízio ES, Lima ACB, Schramski S, Adams C. Social and health dimensions of climate change in the Amazon. Ann Hum Biol. 2016 Jun;43(4):405-14.

37 Ellwanger JH, Kulmann-Leal B, Kaminski VL, Valverde-Villegas JM, Veiga ABG, Spilki FR, et al. Beyond diversity loss and climate change: impacts of Amazon deforestation on infectious diseases and public health. An Acad Bras Ciênc. 2020 Apr;92(1):e20191375.

38 Vidal-Cuellar CL, Chicmana-Zapata V, Arotoma-Rojas I, Meza G, Ford JD, Rodríguez Ferruchi H, et al. Pathways to strengthen the climate resilience of health systems in the peruvian Amazon by working with Indigenous leaders, communities and health officers. BMJ Glob Health. 2024 Sep;8(Suppl 3):e014391.

39 Novais IR, Coelho CO, Machado HC, Surita F, Zeferino LC, Vale DB. Cervical cancer screening in brazilian Amazon indigenous women: towards the intensification of public policies for prevention. PLoS One. 2023 Dec;18(12):e0294956.

40 Borges MFSO, Koifman S, Koifman RJ, Silva IF. Cancer incidence in indigenous populations of western Amazon, Brazil. Ethn Health. 2022 Aug;27(6):1465-81.

41 Sarmiento-Medina MI, Velásquez-Jiménez CM, Ortiz-Hernández N. Experiences of a group of indigenous women from the colombian Amazon with cervical cancer prevention screening. Qualitative study in the context of participatory research to reduce inequalities. Ethn Health. 2024 Nov;29(8):893-907.

42 Sarmiento Medina M, Ardila Sierra A, Quintana González E, Vargas Cruz S, Velásquez Jiménez C, Puerto Amaya M, et al. Intercultural and participative strategy for prevention of cervical cancer in indigenous people. Eur J Public Health. 2020 Sep;30(Suppl 5).

43 Uyttersprot T, Janssens F, Fernandes D, Zhang WH. Exploring the link between oil exploitation and cancer in the indigenous population of Ecuador: a scoping review. Int J Environ Res Public Health. 2022 Feb;19(5):2674.

44 Sarmiento-Medina MI, Amaya MP, Villamizar-Gómez L, González-Coba AC, Guzmán-Barajas L. High-risk HPV prevalence and vaccination coverage among indigenous women in the colombian Amazon: implications for cervical cancer prevention. Cross-sectional study. PLoS One. 2024 Feb;19(2):e0297579.

45 Aguiar KEC, Oliveira IS, Cohen-Paes AN, Coelho RCC, Vinagre LWMS, Rodrigues JCG, et al. Molecular profile of variants in CDH1, TP53, PSCA, PRKAA1, and TTN genes related to gastric cancer susceptibility in Amazonian indigenous populations. J Pers Med. 2023 Sep;13(9):1364.

46 Leitão LPC, Monte N, Rodrigues JCG, Freitas LM, Ribeiro-dos-Santos AM, Ribeiro-dos-Santos Â, et al. Severe toxicities in Amazonian populations and the role of precision medicine in acute lymphoblastic leukemia treatment. Sci Rep. 2024 Nov;14:29344.

47 Horton R, Lo S. Planetary health: a new science for exceptional action. Lancet. 2015 Nov;386(10007):1921-2.

48 Li AML. Ecological determinants of health: food and environment on human health. Environ Sci Pollut Res. 2017 Apr;24(10):9002-15.

49 Buse CG, Hancock T, Allison S, Astle B, Cole D, Fumerton R, et al. Where are the ecological determinants of health? Can J Public Health. 2023 Feb;114(1):152-3.

50 Johnson S, Corbin S, South C, Cawich S. The impact of environmental health determinants in surgical oncology. J Surg Oncol. 2024 Dec;130(7):1439-46.

51 Oswald TK, Langmaid GR. Considering ecological determinants of youth mental health in the era of COVID-19 and the anthropocene: A call to action from young public health professionals. Health Promot J Austr. 2022 Apr;33(2):324-8.

52 Salgado M, Madureira J, Mendes AS, Torres A, Teixeira JP, Oliveira MD. Environmental determinants of population health in urban settings. A systematic review. BMC Public Health. 2020 Jun;20:853.

53 Simon-Kumar R. 'Ecological determinants' of health in the global south: practising sustainable consumption in Kerala, India. Health Promot Int. 2023 Jun;38(3):daac026.

54 Vold L, Wallar L, Papadopoulos A. An evolution in health professional education: the ecological determinants of health. Int J Health Promot Educ. 2022;60(2):102-13.

55 Sebastián MS, Armstrong B, Córdoba JA, Stephens C. Exposures and cancer incidence near oil fields in the Amazon basin of Ecuador. Occup Environ Med. 2001 Aug;58(8):517-22.

56 Rougeon M, Mota C, Trad L. Environmental racism and environmental justice: decolonial inflections and new agendas in Latin America and Brazil. J Polit Ecol. 2023;30(1):699-715.

57 Garnelo L. Especificidades e desafios das políticas públicas de saúde na Amazônia. Cad Saúde Pública. 2019;35(12):e00220519.

58 Nogueira LM, Yabroff KR. Climate change and cancer: the environmental justice perspective. J Natl Cancer Inst. 2024 Jan;116(1):15-25.

59 Silva HG, Requia WJ. Racial and economic disparities in high-temperature exposure in Brazil. Int J Environ Res Public Health. 2025 Jan;22(2):200.

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