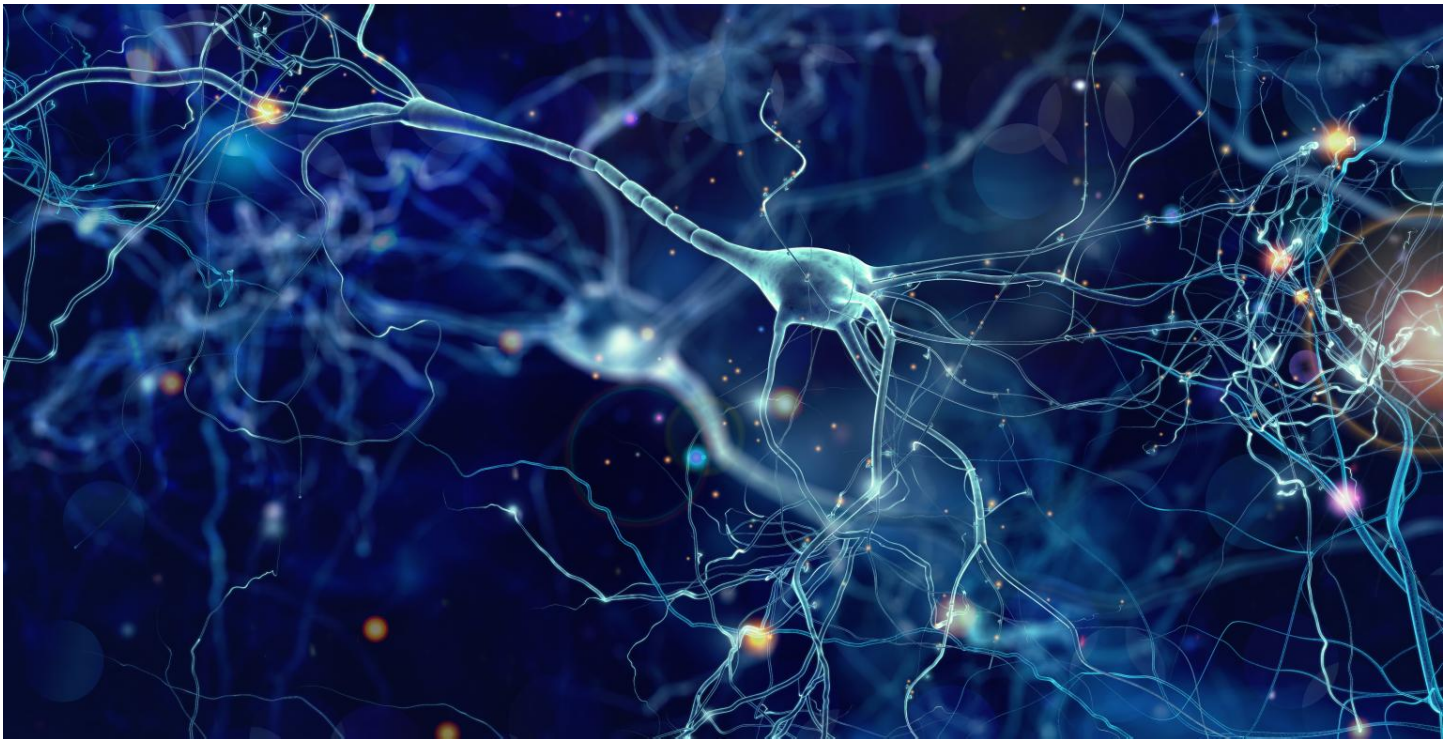

Center for Health and Biosciences | Center for Energy Studies | Research Paper

Brain Capital is Key to a Sustainable Future

July 10, 2023 | Harris A. Eyre, Rachel A. Meidl

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Abstract

Sustaining our planetary future requires a world with clean water, affordable energy, reduced carbon and methane emissions, reduced habitat loss, eradication of poverty, reduction of global inequalities, and quality — as well as equitable — medical care and education. Achieving these endpoints requires innovation, systems thinking, and ultimately, mass human behavior change. This is attainable by fostering a clear scientific and economic evidence base, coordinated and diverse leadership, sustained motivation, and the right mindset and public messaging. Brain capital is a novel framework that recognizes brain skills and brain health as indispensable drivers of the modern knowledge economy. The concept of "green brain capital" — which we are scoping in this paper — places a central emphasis on the brain to deliver a healthy and sustainable environment and, vice versa, on a green environment to promote and safeguard brain health. The environmental determinants of brain health are foundational to this model, as brain health is key to navigating the modern world and thriving. Key brain skills include green skills, creativity, adaptability, digital literacy, and ecological intelligence. Green brain capital intends to be politically pragmatic, economically aware, and lifespan-focused. Growing green brain capital will require transformations across hierarchical levels in social-ecological systems, ranging from individuals to sub-populations to entire societies.

Introducing Brain Capital

Brain capital is a novel framework that recognizes brain skills and brain health as indispensable drivers of the modern knowledge economy (Smith et al. 2021). In economics, brain capital is noted as a productive and complex capital stock that accumulates over the lifecycle (Brain Capital Alliance n.d.). Brain capital is the combination of knowledge, skills, competencies, and tools to achieve, maximize, and sustain brain health and pertains to both individuals and communities. The

world increasingly relies on brain capital, where a premium is put on brain skills (for example, an individual's cognitive, emotional, and social brain resources) and brain health (Lundbeck.com n.d.). Investing in ways to build brain capital is thus fundamental to meet modern societal challenges and to drive innovation globally (World Health Organization 2022a). Since we established the Neuroscience-inspired Policy Initiative within the New Approaches to Economic Challenges group of the Organization for Economic Co-Operation and Development, brain capital has been profiled at the United Nations General Assembly and in major public and private sector reports (Euro-Mediterranean Economists Association n.d.; Organization for Economic Co-operation and Development n.d.).

Sustainability issues are a major contemporary global concern, predicated on a complex set of inseparable and interconnected environmental, societal, historical, institutional, and economic factors (United Nations Department of Economic and Social Affairs n.d.). Strategies to date have been slow to effect change toward environmentally constructive, science-based, sustainable or green approaches and, for the most part, have proven insufficient. This, in part, stems from their failure to account for individual and collective human psychology, particularly through understanding the drivers and motivations underpinning human behavior (Chang 2020).

Planetary health links two of the biggest challenges for humanity — promoting human health and halting environmental degradation. This emerging field recognizes these inter-linkages and promotes creative action-research and interdisciplinary solutions that protect human health and the health of the ecosystems on which we depend (The Lancet Planetary Health 2017). In this paper, we extend this transdisciplinary approach, focusing on the linkages between brain health and the environment.

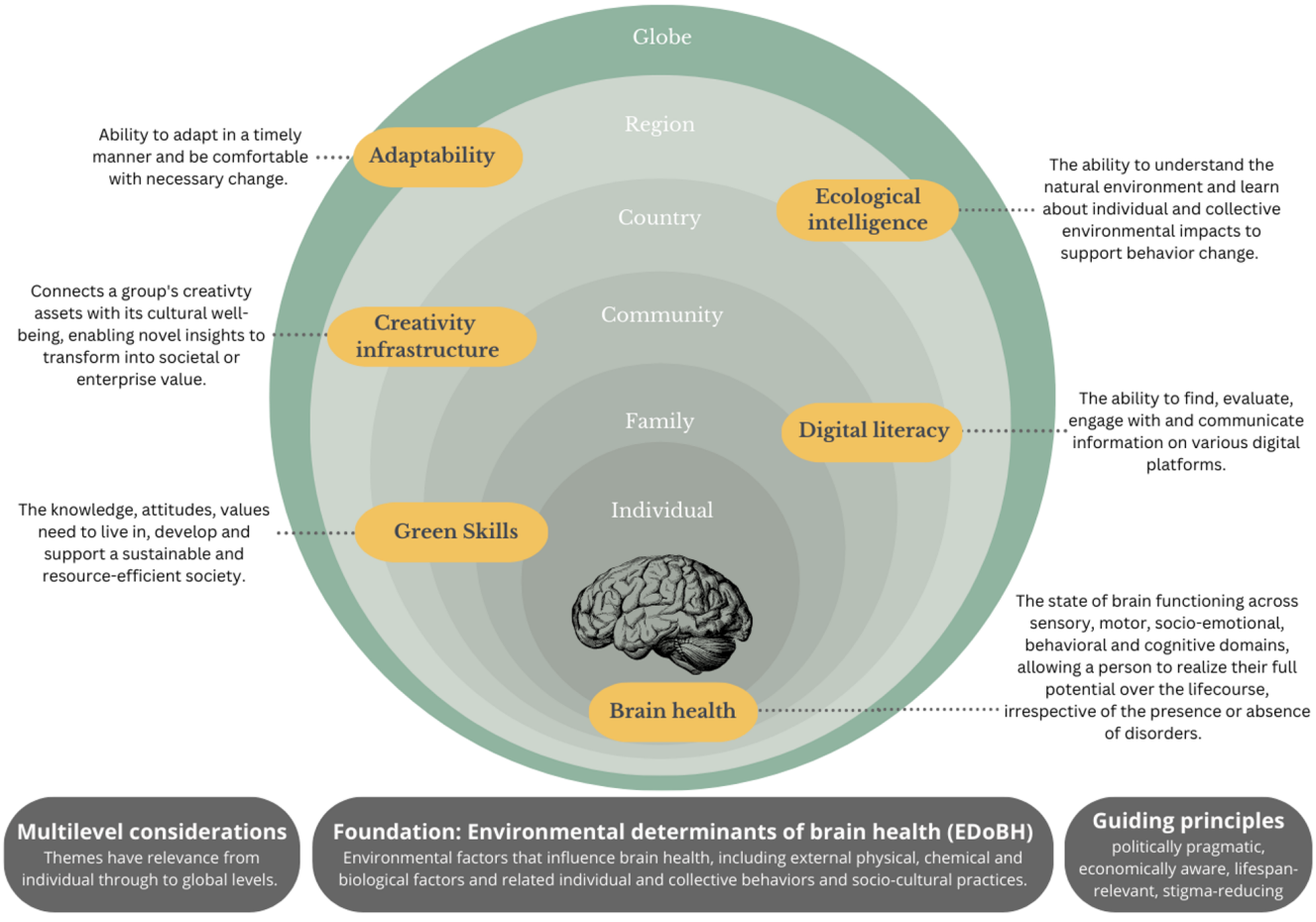
Proposing the Green Brain Capital Model

The green brain capital model is a sustainability-focused type of brain capital. Figure 1 provides an overview of the green brain capital model components:

- Brain health
- Green skills
- Creativity infrastructure
- Ecological intelligence
- Digital literacy
- Adaptability

Throughout this paper, we will examine the inter-relationships between these components. Green brain capital intends to be politically pragmatic, economically aware, and lifespan-focused. Growing green brain capital will require transformations across hierarchical levels in social-ecological systems, ranging from individuals to sub-populations to entire societies. This requires an "in-all-policies" approach.

Figure 1 — Overview of the Green Brain Capital Model



Note This figure represents the green brain capital model. The environmental determinants of brain health (EDoBH) are foundational and determine brain health. The state of brain health determines how well key brain skills (i.e., green skills, creativity infrastructure, adaptability, digital literacy, and ecological intelligence) can flourish in an individual and in a collective. The presence of these brain skills will determine the environmental conditions that are determinative of brain health; hence there is a feedback loop. Guiding principles and multi-level considerations are noted.
Source Figure and legend created by the authors.

Brain Health

Brain health is indispensable to good overall health and well-being across the life course. Recognizing the criticality of fostering brain health globally, the World Health Organization (WHO) launched a position paper in 2022: It formally defines brain health as "the state of brain functioning across cognitive, sensory, social-emotional, behavioral and motor domains, allowing a person to realize their full potential over the life course, irrespective of the presence or absence of disorders." (WHO 2022a).

Brain health does not necessarily imply the absence of disorders (neurological, psychiatric, neurodevelopment, neuroinflammatory, and neurodegenerative). Rather it includes the ability of individuals who are living with a brain disorder to thrive, and for those who do not have a disorder to pursue good health and well-being (Lundbeck.com n.d.). Protecting and optimizing brain health across the lifespan is essential for educational, workplace, and social engagement (i.e., factors critical to individual happiness and well-being, self-actualization and self-efficacy, active societal participation and purpose, and, ultimately, the fulfillment of one's own individual and collective potential). The strong view of this author alliance is that as green brain capital becomes mainstream in the policy and scientific literature, it should be defined equivalently, not only by the reduction or absence of negative impact, but also by the enhancement of positive impact and value, both at the individual and population levels. Figure 2a outlines how brain health interrelates with other green brain capital components.

Crucial to the success of green brain capital and its application to robust policy and economic interventions will be the qualitative and quantitative assessments of its core aspects, which will afford measurement and evaluation of impact. There are already many initiatives underway to characterize and quantify the conceptually broad notion of brain health at both individual and societal levels and across a multitude of sectors. For example, the WHO brain health position paper (WHO 2022b) provides a conceptual framework for brain health and describes how it can be optimized throughout life with actions across the following clusters of determinants: physical health, healthy environments, safety and security, learning and social connection, and access to quality services. By way of illustrative example, Cohen Veterans Bioscience has established the Brain Health Nexus, which is developing a "Scientific and Technology Roadmap" for collective action to combat the growing burden of brain disease (Cohen Veterans Bioscience n.d.). This is a collaborative data-driven effort, consisting of pillars that will be established and expanded with input from the Steering Committee and Brain Health Nexus Summit participants. Input will be gathered from current brain health literature, surveys, and interviews toward the development of a white paper with recommendations for progress. Together, these efforts will lead to an integrated call to action.

Relatedly, the Mental Wealth Initiative, established by the Brain and Mind Centre at The University of Sydney, is working toward structural evolution — changing the social and economic structures that have given rise to the conditions that negatively impact brain capital and the collective well-being of societies (Occhipinti et al. 2022; Occhipinti et al. 2023). "Mental wealth" is a new measure that seeks to modernize gross domestic product to capture more holistically the value generated from both economic and social productivity, which underpins community cohesion, social stability, and system resilience. This transdisciplinary initiative aims to understand the extent to which policy-mediated changes in economic, social, environmental, and health sectors could enhance brain capital and the prosperity of communities, cities, and nations.

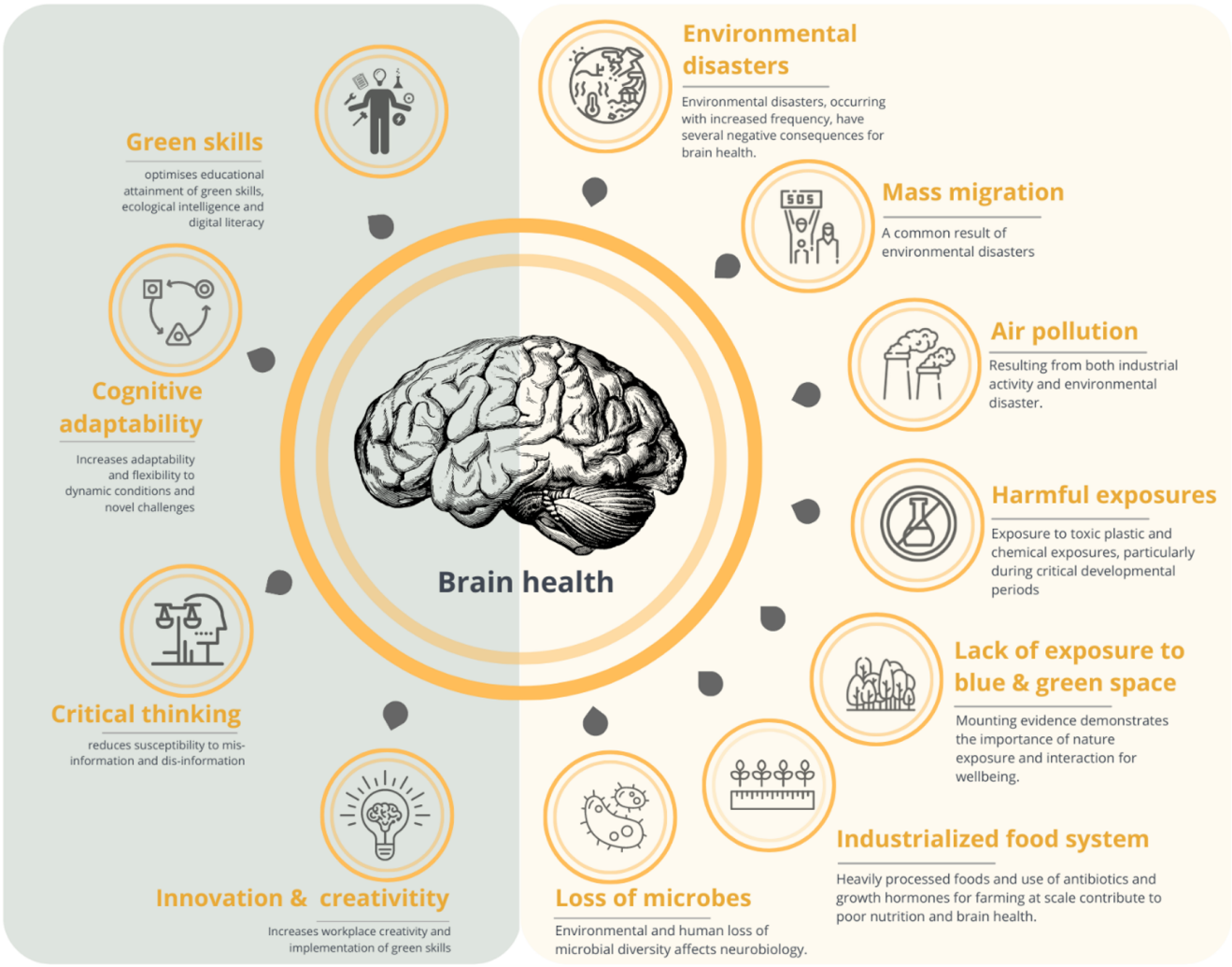
We suggest that these initiatives can and should be complemented by adding a "green dimension" to the optimization and safeguarding of brain health within

our planetary ecosystem. For instance, the **COP2 (Care of People and Planet)** group of climate and mental health organizations is collaborating to recommend mental health action for nations as an integral part of their climate response. Another example includes the **Wellbeing Economy Governments partnership**, which is founded on the recognition that "development" in the 21st century entails delivering human and ecological well-being. Finally, we applaud the recent **Bridgetown Declaration on Noncommunicable Diseases (NCDs) and Mental Health** which we launched to address these issues in small island developing states (SIDS), which are especially at risk. This declaration outlines bold steps to address the range of social, environmental, economic, and commercial issues that lead to NCDs and mental health conditions. Developed through an inclusive process led for and by SIDS, the declaration highlights that NCDs and mental health conditions cannot be properly addressed without responding to the climate crisis. While a wide spectrum of possibilities exists for building this green dimension (and those possibilities will evolve alongside the engagement of all relevant sectors to this new discipline), in this paper we highlight several priority examples in support of a green brain capital model.

Figures 2a & 2b — Brain Health Interactions with Green Brain Capital Components and Environmental Determinants of Brain Health (EDoBH)

Environmental Determinants of Brain Health (EDoBH)

The reciprocity between brain health and the environment has been increasingly recognized (Obradovich et al. 2018; Ruszkiewicz et al. 2019). For instance, increasing societal eco-anxiety and mental health consequences of climate-related disasters (e.g., related to immediate impacts of environmental catastrophes such as tornadoes, severe and prolonged heat waves, and megafloods) and challenges such as water insecurity constitute direct socio-



Source Figures and legends created by the authors.

environmental determinants of brain health, with potentially lasting negative impacts (Albrecht et al. 2007; Cissé et al. 2022; Clayton 2021; Léger-Goodes et al. 2022; Lundbeck.com n.d.; Soutar and Wand 2022; Young et al. 2022). At a population level, such catastrophes may result in substantial long-term sequelae[1] for whole societies, including the sequelae of trauma, forced displacement, mass migrations, famine, and violent and armed conflicts (Romanello et al. 2022; United Nations High Commissioner for Refugees n.d.). Climate change-related brain health challenges are more accentuated in low- and middle-income populations who are disproportionately impacted by climate change and have less resilience and resources to cope. Moreover, climate-related effects on physical health, including increased incidence of communicable diseases (as a consequence of changing ecosystems and spread of pathogens that replicate more rapidly in a climate-dependent way), may ultimately affect brain health (The Lancet Countdown). This may be due to

myriad factors such as the psychosocial sequelae of physical illness, financial distress associated with loss of productivity, and displaced societal resources away from mental health priorities in favor of physical health emergencies, to name but a few. Additionally, a considerable proportion of the burden of brain diseases can be attributed to environmental pollution resulting from human activity. According to the European Environment Agency (2020), mental, behavioral, and neurological conditions are the **fifth leading disease area** with deaths attributable to environmental risk factors such as air pollution.

Another key determinant of both physical and planetary health is the current global industrialized food system, with the economic, environmental, and health costs estimated at nearly $20 trillion per year, with more than half of this attributed to the impact on human health of unhealthy diets (Hendriks et al. 2021; World Economic Forum 2022; Eyre et al. 2023). This is directly relevant to brain health; although not yet captured in global cost or burden estimations, extensive literature from the new field of nutritional psychiatry finds that an unhealthy diet can have a substantial impact on mental and brain health. Evidence across countries and cultures consistently links healthier dietary patterns (i.e., diets higher in plant foods and lower in industrialized foods) to better mental health, independent of socioeconomic and other key factors (e.g., Lassale et al. 2019). Randomized controlled trials addressing diet quality also show improvements in subsyndromal and even severe depressive illnesses (Firth et al. 2019) as well as benefits to cognitive ability (Douglas et al. 2022). Conversely, unhealthy diets are associated with increased risk markers for Alzheimer's disease (Hill et al. 2019) and can rapidly result in impairments to measures of cognitive ability even in healthy young people (Stevenson et al. 2020). Critically, there is evidence for intergenerational effects, with maternal nutrition during pregnancy related to adverse effects on neurodevelopment in children (Borge et al. 2017). While the mechanistic pathways that mediate these effects are many, including immune function, brain plasticity, and neurotransmitter and stress response systems, the unifying role of the human microbiota is increasingly recognized (Cryan et al. 2019; Marx et al. 2021). Given the close link between loss of microbial diversity in the environment and in humans, this again underscores the urgent need to address environmental

health to protect and improve human mental and brain health.

There is also a clear need to better prepare societies to account for the uncertainty inherent in the outcome of global crises. Investing in brain health, and specifically green brain capital, may prove paramount to successfully navigating a future without historical analogues. At COP27, the issue of human resilience was integrated into the United Nations **Race to Resilience** initiative. Moreover, the WHO and the Pan American Health Organization recently introduced the concept of environmental determinants of health (EDHs) as well as the idea that a healthy environment is vital to "ensure healthy lives and promote well-being for all at all ages" (PAHO, n.d). The rapidly growing field of environmental public health addresses global, regional, national, and local environmental factors that impact human health. While this progress is encouraging, we argue that priority attention must be placed on investigating and leveraging the "environmental determinants of brain health" (EDoBH) that are embedded within our proposed green brain capital model. See Figure 2b for a graphical outline of EDoBH.

Finally, there are a wide range of strategies for building green brain capital and social-ecological resilience at large including focusing on prevention, developing innovations in clinical and health care services, implementing new technologies and policies, and building awareness. (See these references for further details: Angeler et al. 2022; Eyre et al. 2022.)

Green Skills

Green skills can be defined as the knowledge, abilities, values, and attitudes needed to live in, develop, and support a sustainable, resource-efficient society and planetary ecosystem (Arthur 2022). The transition to a low-carbon, resource-efficient economy requires systemic (i.e., structural and behavioral) changes involving individuals, institutions, and whole societies that will result not only in innovations, but also in changes to production and consumption processes, policies, and business models. Effectively developing, maintaining, and actualizing such skills requires good brain health. The United Nations Industrial

Development Organization has put forward a range of initiatives to develop green skills (Arthur 2022), including a Green General Skill Index, which measures and tracks engineering and technical skills, science skills, operational management skills, and monitoring skills (Vona et al. 2015).

Green Jobs for Youth Pact. To make the transition to a low-carbon, circular, and nature-positive economy, the International Labour Organization recently launched the Green Jobs for Youth Pact, which aims to globally advance youth green jobs through three tracks (International Labour Organization n.d.):

- Employment and entrepreneurship
- Environmental education
- Empowerment and youth partnerships

Green Skill Development for Older Ages. We strongly encourage the exploration of green skill development in older ages, given increasing lifespans and the trend of people working later in their lives. We suggest the addition of skills that are related directly to human behavioral psychology and are informed by creative capital and ecological awareness and intelligence. We also recommend the design and incorporation of age-appropriate green skills training in the mainstream curricula for primary and secondary schools, universities, and lifelong learning mechanisms.

Creativity Infrastructure

Crafting innovative solutions to improve performance on global climate targets and overcome existing challenges is paramount to achieving a sustainable planetary ecosystem. Alongside the growing focus on environmental determinants of human health and economic systems, there is also increased interest in creativity as a driver of workforce productivity and enterprise innovation (Amabile 2020; Merseal et al. 2022; Tsegaye and Malik 2019). Creativity is among the top skills for leaders and workers alike (World Economic Forum 2020). Connecting creativity infrastructure development with green brain capital has the potential to offer the global community exponential opportunities for collaboration and commerce through the lens of human flourishing

(VanderWeele 2017).

The built environment (Chatterjee et al. 2021; McCoy and Evans 2002), natural environment (Williams et al. 2018), and social environment (Amabile et al. 2018) are all critical drivers of creativity in individuals and communities, and can support a strong creativity infrastructure in communities and organizations alike. Because creative performance increases following exposure to images, sounds, and immersive experiences of natural environments, even our increasingly digital lives need not be separated from the positive impacts of nature (Chulvi et al. 2020; McCoy and Evans 2002).

A creativity infrastructure must be intentionally constructed to connect a group's

- **creativity assets** (Beaty and Johnson, 2021; Diedrich et al. 2018; Karwowski et al. 2018; Kashdan et al. 2020) and
- **cultural well-being** (Acar et al. 2021; Bai et al. 2017; Demerouti et al. 2001; Edmonds et al. 2021; Hacker 2008; Lee 2021; Lister et al. 2021; Mashek and Tangney, 2007; Mishra and Morrissey, 1990; Petrou et al. 2018; Strauss et al. 2016; Tang et al. 2021; Thoroughgood and Webster 2021).

This will enable novel insights to transform into societal or enterprise value.

Creativity infrastructure is not the same as a creative economy (Florida and Seman 2020) and offers a unique alignment opportunity for cross-sector priorities, like the United Nations Sustainable Development Goals (Ayton-Shenker 2021). This could happen through a common set of human factors identified by the World Economic Forum as the top human, non-technical skills that will be required for the future (World Economic Forum 2020) across every sector. Perhaps most importantly for the resilience of national and global markets, creativity infrastructure connects creativity and well-being as mutually reinforcing prerequisites (Amabile and Pratt 2016; Lister et al. 2021) for innovation across art, science, technology, and business. In this sense, creativity becomes the science of connection across all disciplines.

One example of this connection is found in business entrepreneurship. For example, after waning for decades in the U.S., entrepreneurship has grown

significantly since the beginning of the COVID-19 pandemic, according to data from the U.S. Census Bureau. This growth can potentially lead to a more resilient economy if such gains can be sustained.

Researchers have documented (Freeman et al. 2019) that many entrepreneurs are neurodiverse people with differences in mental function who contribute to our social and economic progress as they introduce new products and services and make possible our shared prosperity. These creative and innovative business builders experience a high prevalence of diagnosable mental health issues, and their decision-making processes are often irrational (Freeman et al. 2019). Despite — or more likely because of these differences — entrepreneurs create 80% of net new jobs and are the main drivers of economic growth and development in most modern economies (Strangler and Litan 2009). This example from the vocational sector of business entrepreneurship demonstrates the value of diversity in the brain capital model.

Looking to the future of work, all industry sectors will increasingly depend on human creativity. The group performance of creativity is intertwined with the well-being and flourishing of creators in the cultural, technological, and economic ecosystems. By integrating these perspectives, a creativity infrastructure pillar within green brain capital connects to a broader economic, urbanist, and social infrastructure, enabling work and innovation across all sectors.

Ecological Intelligence

Ecological intelligence is the ability to understand the natural environment and realize the impact of each person on the environment in order to change behavior and live more sustainably (Goleman, 2010; McBride et al. 2013). It includes components such as curiosity about the interaction between humans and ecology, affinity for sustainable eco practices, empathy for future generations, awareness of the consequences of unfriendly climate actions, and long-term thinking. There is an emerging literature on approaches to develop ecological intelligence across the lifespan (Okur-Berberoglu 2020), beginning in

elementary schools (Zulfikar et al. 2020). Novel approaches include combined art-science projects that can facilitate the learning process by appealing both to people's logic and emotions (Scheffer et al. 2015). Stimulating both psychological domains may be a suitable means of creating a more effective ecological intelligence and may also boost people's creative capital and skills. To achieve successful green brain capital, it is necessary to start educating and increasing awareness in the youngest generation with the aim of eventually enabling a paradigm shift, transforming societal perceptions of the consequences of climate change.

Ecological Intelligence Scale. The Ecological Intelligence Scale has recently been developed and can be useful for assessment (Okur-Berberoglu 2020). It includes measures of holism, social intelligence, and economics. These measures make clear that the creation of ecological intelligence operates simultaneously at the individual, organization, and society levels. The scaling up from individuals to higher levels is crucial for achieving societal change, which in turn can cascade down to further spur change at the individual level. It is important to account for potential limitations in this process, particularly regarding ethnic, cultural, social, and language differences among respondents.

Digital Literacy

The development of digital literacy and digital competencies are widely recognized as essential in an increasingly digitized world. Mis- and disinformation are widely known to plague the climate debate (d'I Treen et al. 2019). Digital literacy has previously been defined by Hobbs (2010) as "a constellation of life skills that are necessary for full participation in our media-saturated, information-rich society." Hobbs went on to note digital literacy includes the ability to do the following:

1. Make responsible choices and access information by locating and sharing materials and comprehending information and ideas.
2. Analyze messages in a variety of forms by identifying the author, purpose, and point of view, and evaluating the quality and credibility of the content.

3. Create content in a variety of forms, making use of language, images, sound, and new digital tools and technologies.
4. Reflect on one's own conduct and communication behavior by applying social responsibility and ethical principles.
5. Take social action by working individually and collaboratively to share knowledge and solve problems in the family, workplace, and community, and by participating as a member of a community.

The European Union has developed a Digital Literacy Index to measure and track such skills across 27 countries (ec.europa.eu n.d.). These skills serve as a key indicator of the EU's Digital Decade initiative to fuel digital transformation by 2030 (European Commission n.d.). Large-scale programs aimed at boosting digital literacy include the EDISON Alliance of the World Economic Forum (The EDISON Alliance n.d.) and the **Reskilling Revolution** (Cann 2020).

Climate Misinformation and Disinformation. Within the digital realm, interdisciplinary researchers are studying the field of climate misinformation (i.e., unintentional sharing of false or misleading information) and disinformation (i.e., deliberate sharing of information designed to discredit), which has the potential to fuel climate alarmism and climate denial (d'I Treen et al. 2019; and College of Staten Island 2022). Work is underway to track the sources of misinformation and disinformation — including those who finance, produce, and amplify such information — as well as the characteristics of how it spreads online via social networks, including the role of echo chambers[2] (d'I Treen et al. 2019; Lewandowsky 2020). Cognitive biases[3] also play a role in susceptibility to climate misinformation (Zhao and Luo 2021).

There is an emerging field exploring the intersection of brain health and misinformation susceptibility and resilience.

- **Despair** has been suggested as an underlying factor in the misinformation crisis in the United States of America (Graham n.d.).
- There is an emerging body of research demonstrating that **depression**, underlying a bias toward negativity, may exacerbate the spread of misinformation (Perlis et al. 2022).

- Further, there is active exploration of the role of **cognitive aging** on misinformation susceptibility and resilience (Ternes et al. 2020).

A recent study noted that older adults are no more likely to fall for fake news than younger adults (Pehlivanoglu et al. 2022) and that age-related susceptibility to deceptive news was only evident in those categorized as the "oldest old" (over the age of 85). Aging was found to be associated with a broader knowledge base, more life experience, often a more positive affect, and more time to consume news. However, the researchers postulate that the "oldest old" are more susceptible to misinformation as these protective factors cannot fully compensate for their cognitive declines.

A range of solutions are likely required to combat climate misinformation and disinformation spanning educational, technological, regulatory, and psychological domains (Buchholz, DeHart, and Moorman 2020; Cook et al. 2022; Hornsey and Lewandowsky 2022; Tiernan 2022).

Adaptability

Even though we address adaptability throughout our discussion of the other green brain skills, here we summarize the main features of this component. Adaptability is the capacity to adjust one's thoughts, behaviors, and strategies in response to changing circumstances. This skill is critical in the context of the green brain capital model, where transformations across various levels of social-ecological systems, ranging from individuals to entire societies, are necessary to foster sustainability (Park 2020).

Adaptability underpins our ability to thrive amidst complex and evolving challenges such as climate change, ecological deterioration, and the transition towards a more sustainable economy. It aids in navigating the fluid landscape of green jobs, supports the development and application of green skills, and plays a crucial role in creating innovative solutions necessary for environmental sustainability. In a world where climate and social conditions are constantly changing, adaptability can be seen as a form of meta-skill, enhancing our capacity to learn new skills, unlearn outdated ones, and relearn skills in new

contexts (Zhou and Lin 2016). It also fosters resilience in the face of adversity and the ability to seize opportunities.

The cultivation of adaptability has the potential to bridge the gap between ecological intelligence and action. Adaptability is crucial for individuals and equally relevant at organizational and societal levels. It is a cornerstone for businesses, institutions, and societies seeking to transition towards more sustainable practices (Park 2020). From changing business models to accommodate green technologies to adjusting institutional practices to foster green skills to shifting societal norms in favor of more sustainable behaviors, adaptability is critical. Promoting adaptability involves fostering a culture that encourages flexibility, openness to change, and continuous learning.

Factors That May Limit the Development of Green Brain Capital

Critically, building green brain capital will require the identification of trade-offs, factors that may limit, directly or indirectly, the full development of this asset. In this section we discuss several examples of these factors.

Over-consumption of Natural Capital

Natural capital is a term for the world's stock of natural resources — renewable and non-renewable — and includes plants, animals, air, water, soils, minerals (United Nations System of Environmental Economic Accounting n.d.). Some natural capital assets such as forests and oceans provide people with free goods and services, often called ecosystem services. All of these underpin our economy and society, and thus make human life possible. However, when people act according to their own self-interest instead of the common good of all users, this can lead to resource depletion.

Climate Anxiety and Solastalgia

The uncertainty characteristic of adolescence and early adulthood has, in recent

years, been heightened by pandemic-induced social isolation, social media, economic headwinds, and eco-anxiety, creating a real mental health crisis in young people. Eco-anxiety affects the daily lives and functioning of nearly half of the children and young people worldwide, who often blame government inaction for not doing enough to protect them (Hickman et al. 2021; Léger-Goodes et al. 2022; Soutar and Wand 2022).

In a similar way, the concept of solastalgia defines the distress that is produced by environmental change impact, which is directly connected to the home environment (Albrecht et al. 2007). Solastalgia is particularly acute for Indigenous peoples who have a customary and spiritual linkage to their "place" (Galway et al. 2019).

A recent study noted that climate anxiety positively predicts some pro-environmental actions (Whitmarsh et al. 2022). This survey was conducted on 1,338 U.K. adults and focused on climate anxiety, risk factors, and predictors of action. Climate anxiety was high among younger age groups, as well as those with higher climate concern, higher generalized anxiety, higher connections with nature, higher climate change information-seeking behaviors, and lower mindfulness. This study suggests that climate anxiety may be a motivating force for action.

The "Triple Toxicity" of the Tropics

Certain geographical areas are more directly and profoundly subjected to the impact of the environment on brain health than others. In tropical regions worldwide, a unique combination of environmental risk factors, known as the "triple toxicity," poses a particular threat to brain health and the optimal utilization of brain capital (Berger et al. 2015; Sarnyai et al. 2016).

- **Biological toxicity** is driven primarily by infectious and parasitic diseases, but increasingly environmental pollutants are contributing.
- **Psychosocial toxicity** is brought about by long-term stress — caused by socio-economic disadvantage, discrimination, the impact of displacement, and refugee status — and trauma, often caused by experiencing civil wars

and other forms of violence.
- **Ecological toxicity** is mainly driven by climate change, which disproportionately affects tropical nations. Disaster-related stress is caused by extreme weather events and rising ocean levels, which threaten the existence of some Pacific Island nations.

It is likely that the long-term, devastating impact of this triple toxicity may contribute to economic underdevelopment among tropical countries. In 1892, the gross national product (GNP) per capita in tropical regions was roughly 70% of GNP in the temperate zone. By 1992, GNP per capita in the tropical regions was 25% of that in the temperate zone (Sachs 2001). Nowhere is it more important to build brain health and green brain capital than in the world's tropical zone, where only two countries (out of more than 125) are classified as high income by the World Bank.

Natural and Human-made Contributors to Climate Change

Energy Transition Concerns. To attain de-carbonization and de-methanization and develop robust renewable energy sources, global society will have to use transitional fuels, and these fuels must be affordable. Moreover, a careful transition phase is required.

- If the transition is too slow, then climate challenges — and the associated consequences — will intensify.
- If the transition is too rapid, we risk draining precious capital from other health and human rights priorities.

Natural Runaway Climate Change Effects. In addition to concerns about the speed of transition from fossil energy sources, potential natural "runaway"[4] climate change effects such as permafrost thawing and wildfires at massive scales could simultaneously magnify greenhouse gas emissions and reduce carbon capture efforts.

The challenge for green brain capital building is to embrace a potential future where the current climate will no longer be tenable (Schröder and Storm 2020).

This will require preparation for and adaptation to a “hothouse” earth. At this point, returning to a more benign climate for humans will be impossible, as many tipping points of planetary boundaries in the atmosphere, cryosphere, and aquasphere may have been irreversibly passed (Steffen et al. 2018). We suggest that green brain capital can be a useful addition to the earth stewardship framework (Chapin III et al. 2011). This involves shaping trajectories of socio-ecological change from local to global scales to enhance ecosystem resilience and human well-being, and for navigating potential critical transitions in the Earth’s climate.

Effects of Environmental Toxins on Our Brains

Humans may encounter a staggering 80,000 or more toxic chemicals as they work, play, sleep, and learn — so many that it is almost impossible to determine their individual effects on a person, let alone how they may interact or their cumulative impact on the nervous system over a lifespan. Mounting evidence from environmental neuroscience research has demonstrated the harmful impacts of environmental toxins to brain health (Liu et al. 2023; Tamiz et al. 2022), including direct links to increased risk of Parkinson’s disease (Pezzoli and Cereda 2013) and Alzheimer’s disease (Finch and Kulminski 2019).

Current evidence indicates that micro- and nanoplastics can be ingested by aquatic organisms as well as by mammals (Prüst et al. 2020). Upon uptake, micro- and nanoplastics can reach the brain, although there is limited information regarding the number of particles that reach the brain and the potential neurotoxicity of these particles. Similarly, persistent organic and heavy metal pollutants are ubiquitous, and some — like phthalates, organophosphates, and polychlorinated biphenyls (PCBs) — have known, negative effects on human behavior and brain health (Berk et al. 2014). A systematic comparison of the neurotoxic effects of dissolved matter and different particle types, shapes, and sizes at different exposure concentrations and durations is urgently needed to further clarify the neurotoxic hazard and risk of exposure to pollutants and micro- and nanoplastics.

Studying the Exposome. In this context, the "exposome" is of growing concern. The term refers to "the measure of all the exposures of an individual in a lifetime and how those exposures relate to health" (Centers for Disease Control and Prevention 2022).

Currently, there are some initiatives to study the totality of exposures and link them to internal changes in different body systems, including the brain, with special consideration of the length of exposures (Graham et al. 2022). The present exposome initiatives are disease-centered, for example, trying to evaluate the possible exposomic fingerprint for Alzheimer's disease (Vineis et al. 2017). However, with the broader understanding of brain health as exceeding the mere absence of disease, it seems feasible to consider an atlas or "reference exposome"[5] and correlate it to brain health in general populations (Turner et al. 2018). This is a timely approach, especially for low- and middle-income countries that are moving from agricultural to industrial economies, as nature and temporality of exposures are changing. Better appreciation of these dimensions will help to assess the contribution of the environment to brain health.

In addition to studying the exposome, there are many other paths to explore in seeking to develop and garner support for green brain capital — in the next section we highlight some of them.

Further Avenues to Explore and Develop

Neuro-urbanism

In socio-ecological systems, humans influence and are influenced by ecosystems. There are clear bidirectional interactions between nature and brain capital. Brain health is key to supporting the effective development and deployment of green skills, including sustainability-enhancing engineering and technical skills, science skills, operational management skills, and monitoring skills. Research is underway to study these factors in a transdisciplinary manner, and a knowledge base is accumulating with the emergence of new disciplines and paradigms.

For example, a new field of neuro-urbanism has been proposed. This field spans neuroscience and the urban disciplines including urban planning, architecture, and sociology. It calls for more cross-sectional approaches in different global regions and has led to the emergence of an Interdisciplinary Forum on Neuro-urbanism, which develops novel approaches to optimize the effects of the urban environment on citizen's brains (neurourbanistik.de n.d.). This focus will benefit from increased understanding of the impacts that reimagined environments may have on psychological well-being (von Lindern 2017), including the importance of green space, water features, proximity to living things, and the "sense of being away." Preliminary data suggest that access to nature is key to supporting creative processes for children (Wojciehowski and Ernst 2018) and working professionals (Plambech and van den Bosch 2015).

An example of this research is an intervention study conducted by Sudimac and colleagues (2022) to investigate changes in activation of stress-related brain regions as an effect of a one-hour walk in an urban environment (a busy street) versus a natural environment (forest). Brain activation was measured in 63 healthy young adults before and after the walk, using a "fearful faces" task and a "social stress" task.[6] The authors demonstrated that amygdala activity decreased following one hour of walking in nature. Since the amygdala is the part of the brain associated with emotional processes, these results suggest that going for a walk in nature can have salutogenic[7] effects on stress-related brain regions and, consequently, may be protective against mental strain and stress-related diseases including age-related memory decline. Given the rapid increase of urbanization, such results can inform urban planning to create more accessible green areas and adapt urban environments in a way that will be beneficial for citizens' mental health. There is also evidence of the benefits of nature exposure on cognitive function and hence brain capital and well-being (Vella-Brodrick et al. 2022). While mental health and brain capital can benefit from people engaging with nature, this may also boost their motivation for climate-relevant action.

More generally, the biophilia hypothesis, which postulates that humans have an intrinsic affinity to the natural environment (Wilson 1984), may encourage

building a research agenda focused on creating green brain capital in which ecological, cultural, and technological dimensions can be studied. This work could include spiritual dimensions of ecosystem services for mental well-being and production services required for meeting basic life demands. This is fertile ground for transdisciplinary collaborations to create green brain capital.

Awareness, Education, and Training

As an enabler for the broader policy objectives, and a means to empower individuals and communities to engage with the challenges and opportunities of the future, a comprehensive approach to building literacy through education, awareness, and advocacy should be considered. This should not be limited to sectoral skills and should instead range through the continuum from awareness to new green brain health knowledge and skills. To some extent, this borrows from the models of other public health or social activation approaches — viewing the public education component as a central piece of a "whole society" approach. In this, one can leverage both traditional means of public engagement and literacy building, as well as more innovative and disruptive approaches. The importance of engaging with young people has already been noted (Farina et al. 2023). Equally important to consider is the overall matrix of school programs and approaches developed to both train teachers to understand, develop, and deliver content related to green brain capital and to protect their own brain health and well-being (Harding et al. 2019; Jourdan 2008). By comprehensively enhancing public literacy in tandem with more targeted or sectoral initiatives, we can create the means to enable greater scaling across society while embedding best practices.

Neuroscience, Geopolitics, Diplomacy, and Sustainable Futures

Some countries emit more carbon and methane than others, so the green brain capital model requires the greatest attention in these jurisdictions. China, Russia, and India are the top three methane emitters (Global Methane Pledge n.d.), and China, the United States, India, Russia, and Japan are the top carbon emitters (Friedrich et al. 2020). The global community must support, via diplomatic

means, these countries in their transition to more sustainable economies. We have previously written about a unique form of neuroscience-inspired diplomacy to support the tackling of systemic challenges (Abbott et al. 2022; Dawson et al. 2020). The green brain capital model, once matured sufficiently, can be leveraged in diplomatic exchanges. Benchmarking exercises for green brain capital-related components may also help optimize national and global activities and outcomes.

Conclusion

There is an urgent need to refine and further develop strategies to measure and build green brain capital. We note two prominent implementation frameworks that could be leveraged:

- **The UN Theory of Change Modeling** (United Nations Development Group 2017) — this model explains how a given intervention, or set of interventions, is expected to lead to a specific change, drawing on the causal analysis based on available evidence. A thorough theory of change helps guide the development of sound and evidence-based strategies, with assumptions and risks clearly analyzed and spelled out.
- **The Attitude-Facilitators-Infrastructure framework** (Akenji and Chen 2016) draws from three lifestyle determinants and describes the elements needed to design a sustainable lifestyles policy package at a systems level — focusing on changing the context that shapes lifestyles and addressing the macro factors beyond an individual's control.

The use of a structured Delphi process would also be helpful to refine this model.[8] A three-round Delphi study can be conducted on a global level to identify the current situation, set future goals, and locate the gap that separates us from our final objectives. The experts invited to take part in the study should reflect the diversity of the green brain capital model and the need for a geographically represented consensus. The American University of Cairo has recently funded such a Delphi process, and it will begin in the coming months.

More than half of the world’s population lives in cities, a share that is expected to

reach 60% by 2030 and two-thirds by 2050 (Ekins et al. 2019). This means city-based interventions may be particularly impactful for boosting green brain capital. To this end, a range of models have been developed around "healthy cities" that could be adapted to green brain capital. (For a detailed review, see Hancock and the IUHPE's Global Working Group on Waiora Planetary Health 2021.) The One Planet model is an example, championed by the World Wildlife Fund (WWF) and Bioregional, a U.K.-based consultancy (Bioregional 2016).

Through supporting green brain capital development, we can hope for a better future for our societies and reduce human impact on the natural environment. The brain makes it possible to connect organically with both the environment and the community, thus affecting socio-ecological resilience and enabling us to achieve global sustainability goals and, ultimately, optimize planetary health.

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Endnotes

[1] Sequelae are aftereffects of a disease, condition, or injury, or more generally a secondary result: https://www.merriam-webster.com/dictionary/sequelae.

[2] In an echo chamber people pay attention only to information that fits their views and they ignore information that does not. On social media echo chambers see: https://advertising.utexas.edu/news/what-social-media-echo-chamber.

[3] Cognitive biases lead people to interpret information based on their own experiences and beliefs, which may or may result in an accurate interpretation. For more see https://health.clevelandclinic.org/cognitive-bias/.

[4] For a description of runaway climate change see https://www.climateemergencyinstitute.com/runaway.

[5] The "reference exposome" is an atlas of the exposome based on a vast amount of exposure and multi-omics data ("multi-omics" data includes data generated at many different levels: genome, epigenome, transcriptome, proteome, and metabolome). This tool will allow for network analyses across regions, population demographics, and other properties. It could also allow individuals to compare their exposome data to the reference exposome: see Caspar W. Safarlou, Karin R. Jongsma, Roel Vermeulen, and Annelien L. Bredenoord, "The ethical aspects of exposome research: a systematic review," *Exposome* 3(1), 2023: osad004, https://doi.org/10.1093/exposome/osad004.

[6] In the fearful faces task photos of faces are shown that either look fearful or neutral. This is a task that is commonly used to measure amygdala activity in response to the fearful face.

In the social stress task participants need to complete relatively easy arithmetic tasks but under time pressure. In the stress condition participants receive the

fake feedback that other individuals who took part in the study performed considerably better than they do.

[7] Salutogenesis is "an approach to human health that examines the factors contributing to the promotion and maintenance of physical and mental well-being rather than disease with particular emphasis on the coping mechanisms of individuals which help preserve health despite stressful conditions" (**https://www.merriam-webster.com/dictionary/salutogenesis**).

[8] The Delphi process is a systematic method of forecasting that uses the collective opinion of panel members. For more information on the methodology see, for example: **https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8299905/**.

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