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ORIGINAL RESEARCH ARTICLE

Climate change and emerging pathogens: Toward nature-based solutions

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ABSTRACT

Our planet has experienced several drastic changes in climate during its history. Nonetheless, human activity in the last two hundred years of industrialization has brought about a significant rise in greenhouse gases, which have led to inexorable global warming and climate change, a direct threat to our ecosystem. Global warming is precipitating the thawing of peri-glacial permafrost, which then releases additional greenhouse gasses, which can be toxic to our health, and alter fresh water supplies and crops. Melting permafrost also releases ancient and novel pathogens potentially harmful to human health. This paper outlines certain nature-based solutions that could bring about carbon-neutral energy generation, as well as immune protective interventions.

Keywords: Global Warming; International Commission on Stratigraphy (ICS); Atlantic Meridional Overturning Circulation (AMOC); Carbon Dioxide (CO_2); Global Warming Potential (GWP); Vitamin D Receptor (VDR); Vitamin D_3 (D3); T Helper 1 (TH1); Interleukin (IL)-2; Interferon-gamma (INF-g); Permafrsot; Severe Acute Respiratory Syndrome Corona Virus-2 (SARS-CoV2); Corona Virus Disease 2019 (COVID-19); Translational Environmental Restoration (TER); Autologous Immune Enhancement Therapy (AIET)

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1. From climate change to global warming: Threats to health

1.1 Climate "disruptions"

Our planet has experienced several drastic changes in climate during its history. In the geologic time scale of the International Commission on Stratigraphy (ICS), we are presently in the Quaternary period of the Cenozoic Era, so named by Jules Desnoyers (1840's) after Arduino's early geologic discoveries reported in his second scientific letter.

Our Quaternary epoch follows the Neogene period, and spans about 2.3 million years. It consists of two principal sub-periods—the Pleistocene (2.58 million years ago to 11.7 thousand years ago) and the Holocene (11.7 thousand years ago to the present). It is defined by the cyclic growth and decay of continental ice sheets related to, and associated with dramatic climate and environmental changes[1].

It has been proposed that the current terminal end of the Holocene sub-period should be called the Anthropocene to indicate the significant impact of the human species upon our planetary ecosystem and climate. However, as of 2022, ICS has not formally recognized what some call anthropogenic climate change[2].

The debate centers in part on the fact that there have been several important changes in planetary climate throughout history, which appear to be independent from human cause. Case in point, three centuries between the 950's and the 1250's AD (i.e., the Medieval Climatic Anomaly period) were characterized by abnormally warm currents of the North Atlantic, with consequentially elevated land temperatures across Europe and North America. That period was followed by drastic cooling of the North Atlantic and three waves of particularly cold waves roughly one century apart (about 1650, about 1770, about 1850) with intervals of slight warming. It is possible and even likely that *sequelae* of the Medieval Climatic Anomaly and of what is commonly referred to as the Little Ice Age (1300's–1850's) were felt across the planet well beyond Western Europe and North America. Droughts and cold spells may have altered not only landscapes, but the fauna and flora of entire regions (e.g., sub-sahara region[3]), as well as cultures and populations (e.g., the Mayas[4]).

In brief, planetary climate patterns are dynamic and may have several natural causes that are not anthropogenic. These causal factors include cyclical lows in solar radiation, heightened volcanic activity, changes in the ocean current circulation, variations in the planetary orbit and axial tilt. In fact, the surface Atlantic Meridional Overturning Circulation (AMOC) dynamics is probably one of the principals, if not the main culprit for the Medieval Climatic Anomaly[5].

In brief, AMOC is a dynamic indicator of the health of the oceans, and by extension of the planet. It is a meta-oceanic process that governs global seas, and ensures that salinity, heat and energy are continuously distributed around the planet. In turn, the oceanic flow of AMOC regulates global climate because it acts like a conveyor belt of ocean currents driven by differences in seawater temperature and salt content (i.e., water's density). AMOC pushes warm sea water northwards, and as the water mass cools and surface evaporation occurs, the salt concentration and the water density increase. Denser water sinks to the bottom of the ocean, and less dense water rises. The cold, dense water spreads as a band of current below the surface, and travels southwards before rising again to the surface as it warms, and thus completes the global oceanic water circulation loop[6,7].

During planetary warming periods, melting polar ice caps contribute to increased rainfall, and a progressive weakening of AMOC by raising fresh water flux. The resulting increase flux of fresh water in the oceans alters the oceanic currents, and weakens AMOC[8].

The gradient in oceanic water density drops, AMOC is weakened, and climate on the land masses is affected.

For instance, AMOC brings warmer water to the North Atlantic, which helps ensures Europe has relatively milder winters than North America, despite they both lie about the same relatively high latitude (*i.e.*, New York lies at 40.7128° North, Naples, Italy lies at 40.8518° North). Because of AMOC, Naples never sees—until now, that is—the frigid winters that afflict New York.

A weaker AMOC can and will have grave consequences and significant climate alterations in North and Central America, Europe as wells as along the Atlantic, the Pacific and the Mediterranean coastlines[9–11]. Statistical algorithms predict the effects of sustained weakening in AMOC[12] on climate change: a sustained weakening that will bring it to a tipping point, which could signify its inevitable and irreversible collapse in climatic patterns around the planet.

1.2 Climate change and global warming

It is unarguable that, following the 1850's Industrial Revolution, human activity has contributed significantly to altering natural climatic patterns. Anthropogenic climate change in the last two centuries is real, and is impacting the ecosystem, with clear and distinct threat on human trans-national migrations, socio-political stability, poverty, and health[13–15].

To be clear, the First Industrial Revolution (cca. 1700–1850) used water and steam power to mechanize production. The Second Industrial Revolution (cca. 1850–1950) used electric power to create mass production. The Third Industrial Revolution (cca. 1950–2000) used electronics and information technology to automate production.

But, the current Fourth Industrial Revolution builds on the emergence of the digital era by fusing technologies and blurring the lines between the physical, digital, and biological domains. Billions of people across the globe are connected by mobile devices with unprecedented processing power, storage capacity. Information and mis-information, factual and illusionary knowledge (e.g., fake news) are unlimited. Artificial intelligence, robotics, Internet, autonomous electric vehicles, 3-D printing, nanotechnology, biotechnology, materials science, energy storage, and quantum computing, to mention only a few, are recently established advances designed to improve the lifestyles of each and every individual across diverse societies and cultural groups world-wide.

From the one perspective, industrial revolutions, from the first to the current fourth, have brought progress: economic growth in numerous countries, mounting financial security of several political systems and organizations, increased well-being and lifestyles for millions across the world. From another viewpoint, industrial revolutions have ravaged natural landscapes, farmlands and eco-systems, destroyed small and middle economies, and led to profound alterations in the balance of the ecological variables that determine and control the climate. In fact, starting in the early 1700's, human activity, which we promote as "industrial revolutions for the benefit of humanity", has rapidly and inexorably increased the emission of greenhouse gases to the atmosphere. These gases include, but are not limited to and fluoride gases (perfluoro- and hydrofluoro-carbon gases, sulfur hexafluoride, and nitrogen trifluoride), several of which are implicated in the depletion of the ozone layer, as well as carbon dioxide (CO_2), methane, and nitrous oxide.

It was Foote (1819–1888) who first demonstrated that certain gases warmed when exposed to sunlight, and specifically that rising CO_2 levels could change atmospheric temperature. In her work presented at the 1856 meeting of the American Association for the Advancement of Science, Foote proposed by inference that greenhouse gases could significantly alter climate[16]. Tyndall (1820–1893), Stokes (1819–1903) and Ruskin (1819–1900) confirmed Foote's observations with more complete and elegant experiments a few years later[17].

These greenhouse gases, besides being seriously noxious to human health, and even potentially lethal, create an atmospheric stratum that solar heat reflected from the earth crust cannot cross. Solar heat is thusly captured between the atmosphere above and the earth crust and oceans below, resulting in increased earth-level temperature. Case in point, from 1880 to today, the earth's average surface temperature has risen by 0.07 °C every decade.

With the rise in planetary average surface temperature, comes profound aberrations in climate regulation (i.e., climate change), and the melting of eternal snows, glaciers and polar ice. With emerging significant climate change, which bring about repeated cycles of typhoons and tornadoes, La Niña and El Niño, serious droughts, severe wind storms and uncontrolled flooding at an increasing rate, comes critical shortages of food and drinkable water, climate-driven emergency mass migrations, with the associated threats of social and political unrest, violence and war.

As the planet average temperature increases, polar ice, eternal snows and glaciers thawing may be unstoppable and irreversible. Predictions are that, at the current rate, planetary ice melting could raise ocean water levels by at least 3 meters—over 10 feet—a process that will inexorably reshape existing continents, and drown many coastline cities, such as New York, Miami, Los Angeles, Manila, Barcelona, Saint Petersburg, Athens, Istanbul, Naples, Rio de Janeiro, Amsterdam and many others. Rising sea levels and temperatures are also predicted to lead to dramatic flooding, hurricanes, tsunamis, with constantly rising climate-driven migrations, political unrest, wars, famine, and mental as well as physiological disease[18].

1.3 Climate change threats to health

In brief, climate change, the long-term alterations in the planet's climate and weather patterns, has occurred several times over the past millennia for reasons other than human activity. Over the course of the last two centuries, however, industrialization has accelerated the rise of greenhouse gases that trap solar heat within the atmospheric layer.

The potential of each greenhouse gas to contribute to global warming is estimated as the Global Warming Potential (GWP), which is expressed as the amount of energy the emissions of 1 ton of a gas—

about the weight of a mid-size car—will absorb over a given period of time, relative to the emissions of 1 ton of CO_2. The greater the gas' GWP, the greater its contribution to human activity-mediated climate change.

Increased in average temperature also leads to profound changes in weather patterns at every latitude. Increased periods of serious droughts, increased torrential rains (e.g., atmospheric rivers), increased number and severity of typhoons and cyclones, torrid heat waves and gripping cold spells, lack of Alpine and Himalayan snows and retreating glaciers, melting of permafrost are but of few of the abnormal weather patterns now being experienced around the planet: trends that are anticipated to worsen in the next decade.

Alternating periods of flooding and droughts have serious impact on the quantity and the quality of crops, with consequential depletion in vitamins, minerals and other micro-nutrients. Indeed, the Green Revolution of the 1960's increased agricultural productivity to help satisfy the needs of a fast-growing global population. This effort contributed to the rise in greenhouse gases, which in this specific context impair crop yields and reduce the nutrient content, threatening global food security.

Case in point, there are a multitude of varying factors that contribute to the optimal growth environment for a crop, most importantly temperature and water availability. As global temperatures increase above 30 ℃, a decrease in yield can be observed for rain-fed crops (i.e., wheat, maize, and rice) as exposure to high temperatures causes direct plant cell damage and crop water loss. Moreover, the melting of polar ice caps, increasing water density, and contamination of coastal aquifers and other freshwater pipelines expose crops to harmful chemicals and minerals that lower the nutritional yield. Availability of clean water can fluctuate with the unpredictability of extreme flooding and dry seasons[19].

Chemicals and pathogens can be transported into crops and threaten global food and nutrient security. Climate change can expose crops to aerial inputs of contamination, precipitation variability (i.e., floods and droughts), and exposure to heavy metals in soil composition[20].

For example, various grains, red meats, and oily fish species normally contain amounts of iron and vitamin D which are essential for human health, particularly oral health. Iron deficiency anemia can cause a reduced number of red blood cells that bring vitamins and other necessary nutrients to the gums and teeth. Nutrient deficient crops and livestock with decreased amounts of cholecalciferol, (i.e., vitamin D_3; D3) and iron can result in oral diseases such as dental caries and periodontal disease[21].

To be clear, with vitamin D skin synthesis occurring under the influence of the sun's ultraviolet radiation, for example, inadequate radiation or insufficient cutaneous absorption of sun ultraviolet rays can lead to serious vitamin D deficiency. Vitamin D consists of a group of fat-soluble seco-steroids (seco: Latin, *secare*, to cut), which promote, among others, the vitamin D receptor (VDR)-mediated intestinal absorption of micro-nutrients and minerals, such as zinc, magnesium and phosphate, which are essential for cell physiology (i.e., ergocalciferol and vitamin D_2), or immune regulation (i.e., D3)[22–26].

The VDR is a cytoplasmic calcitriol receptor, which is translocated to the nucleus upon binding to its ligand, where it binds to corresponding DNA responsive element, in a manner akin to glucocorticoids. In the case of cholecalciferol (D3) binding, VDR modulates the suppression of inflammatory immune responses that underlie autoimmunity and promote allergic responses, while boosting innate systemic and mucosal (e.g., oral) immunity against pathogens of bacterial or viral origin, and sustaining memory adaptive immunity[22–26].

D3, via its specific VDR receptor, on suppresses autoimmune and inflammatory conditions in general, and promotes dendritic cell and regulatory T-cell differentiation, and reducing T Helper 1 (TH1) response and inducing TH2, modulating interleukin (IL)-2 and IL-17 action, blunting production of interferon-gamma (INF-g)[22–26].

A recent meta-analysis of twenty-four observational studies containing 3,637 participants demonstrated a potential increased risk of developing severe COVID-19 disease among patients infected with SARS-CoV2 with low D3 levels[27]. However, in a related research synthesis protocol involving three randomized controlled trials and 356 subjects, D3 supplementation was conclusively shown to improve COVID-19 severity outcomes[28]. The role of D3 in the onset and course of the Post Acute CoVID-19 Syndrome (PACS; i.e., Long COVID)[29] is yet to be determined.

2. Melting permafrost

2.1 Nature of permafrost

Global warming causes melting of glaciers and eternal snows at higher altitudes, and the release of large sheets of polar ice into the oceans. On land, extended areas of permafrost are thawing[30–32].

Permafrost is generally defined as the ground where soil temperature remains at or below 0 ℃ for at least two consecutive years. It consists of an upper active layer of frozen soil that may, or may not freeze and thaw seasonally, and a second deeper layer of soil that is largely stable and can remain frozen for centuries. The ratio of active and stable permafrost varies geographically.

Permafrost may entrap as much as 1,500 billion tons of carbon. As it thaws, it releases large quantities of methane, CO_2 and other greenhouse gases, which further contribute to the entrapment of planetary heat in the atmosphere, and exacerbate global warming[31–33].

2.2 Ancient organisms in "eternal" ice

Thawing permafrost occurs at high latitudes, mainly along the banks of rivers and lakes in Siberia, the Tibetan Plateau, Alaska, Northern Canada, Greenland, and Scandinavia. Permafrost, some of which has been frozen for tens or hundreds of thousands of years, stores the carbon-based remains of plants and animals that froze before they could decompose[34–36].

2.3 Novel and ancients pathogens in melting permafrost

Equally as concerning is the observation that permafrost thaw releases ancient and novel pathogens entrapped as sub-zero microbiotome in permafrost ice for centuries[37,38]. Permafrost pathogens include parasites and fungi[39], bacteria[40], as well as DNA[41], RNA[42] and giant viruses[43]. Taken together, the release of novel and ancient pathogens by melting permafrost poses timely and critical challenges to our immune system[44], which is generally ill-equipped to confront new microbes, as the recent and ongoing pandemic confirms.

When faced with a new virus, as was the Severe Acute Respiratory Syndrome Corona Virus2 (SARS-CoV2) virus when is first identified to be responsible for is responsible for the Corona Virus Disease 2019 (COVID-19)[45–47], the immune system typically engages in a multi-pronged response characterized with several areas of overlap and redundancies to ensure prompt and efficient containment of the invading pathogen. When correctly understood, what appears as an immunopathological response (e.g., uncontrolled cytokine storm), often in fact opens new directions to effective immunotherapeutic interventions[47].

3. Toward nature-based solutions

The challenge of the next decade is, of course, to find effective solutions not only to the fast-worsening climate change and global warming, but—and certainly as importantly—to the threat of new and ancient pathogens released by melting permafrost, glaciers and eternal ice and snow to human health and, more generally, to the survival of the human species. We proposed a Translational Environmental Restoration (TER) paradigm[48] for systematic research synthesis of climate change findings, based on research synthesis work in Tasmania[49], and recent advances in evidence-based research[50,51], as a promising tool for identifying and acting upon the bets available findings as they emerge. We sought to apply these principles to the gargantuan problem of plastic, nurdle (i.e., plastic pellet) and micro-plastic pollution of our seas and air, inexorably exacerbated by the large amount of disposed personal protective equipment (e.g., mask materials and gloves gown materials) during the pandemic, which is bound to have catastrophic effects on our atmosphere in the form of non-biodegradable pollutants, and our health in the coming years[52].

Undoubtedly, we will not find effective solution to climate change and global warming so long as we do not attain a point of net-zero carbon-neutral energy supply. The International Energy Agency defines net-zero carbon neutrality as the state of release an amount of CO_2 into the atmosphere balanced by an equivalent amount of CO_2 removed from the atmosphere. As deforestation continues at the present frenetic pace, that goal seems difficult if, not impossible to attain in our generation.

Electricity should be, by definition, the carbon-neutral form of energy *par excellence*. However, the means at our disposal presently to generate electricity—simply described as the stream of charged electrons through a conductor or through space from the initial cathode to a destination anode—are far from being carbon-neutral. Case in point, electro-mechanical electricity generators are traditionally driven by turbines moved by steam produced from fossil fuel combustion. Environmentally cleaner systems generate electricity, including the heat released from nuclear reactions or from other sources, kinetic energy extracted from wind or flowing water, and, more recently, systems designed to capture solar energy and convert it to electrical power by means of photovoltaic cells.

Photovoltaics convert sunlight into an electric current by using lenses, mirrors and solar tracking systems to focus and concentrate solar power into a small beam that can then be converted into electricity. Photovoltaics can now power homes via solar panels, and larger megawatts scale units, such as the Pavagada Solar Park in Karnataka, India, can generate as much as 2,050 megawatts of electrical energy[53] sufficient for a city. At a smaller scale, the Platio Innovations company[54] has combined the photovoltaic technology with the need to clean the environment from dry waste. Used plastic, broken glass and other dry debris are compacted into a substratum of average tile dimension, over which a pressure-resistant photovoltaic cell is applied. About 400 used plastic bottles can be compacted into 1 m^2 (i.e., 10.7 ft^2) of photovoltaic tile, each generating about 20 Watts of electricity. Photovoltaic tiles can be assembled, and easily be replaced individually, if necessary, into roads or driveways to withstand the weight of a fully loaded truck. An average 15 by 15 ft driveway of these photovoltaic tiles can provide enough energy for an average one-family home.

In brief, photovoltaics is rapidly becoming an inexpensive, low-carbon—but not net-zero carbon-neutral—option. In fact, a typical photovoltaic system produces direct current that must be converted to alternating current for common use. In other words, a common photovoltaic system must comprise an arrangement of solar panels to absorb and directly convert sunlight into electricity, an electrical inverter, which of course needs power to run, to change the current from direct to alternating, and the entire setup of mounting brackets, cabling and other electrical accessories. Secondly, photovoltaic production of current from solar energy involves the excitation of negatively charged electrons within a semiconductor medium, which most often involves environmentally toxic titanium dioxide extracted from a titanium-iron oxide mineral itself mined and extracted from titanium ores. That is to say, photovoltaic energy is a low-carbon technology that generates a significant chemical footprint during the manufacturing and disposal process of the photovoltaic cells.

Alternative solutions to generate carbon-clean electricity include tidal waves, which, as efficient as it may seem *prima facie*, is in fact limited by cost and corrosion. Geothermal energy, the heat that comes from the center of the earth, could be a solution as well, if it were not for the not-insignificant danger of releasing deep earth gases, from CO to CO_2, methane, hydrogen sulfide, ammonia and other greenhouse gases trapped in the earth crust.

A promising alternative near net-zero carbon-neutral technology to generate electricity may be microbial fuel cells, which are based on the observation that certain naturally occurring microorganisms have the property of exchanging electrons for their survival. Concerted efforts are being made to harness that ability to exchange of electrons, to induce a flow of electrons, and possibly other subatomic particles, to generate electricity. Case in point, the purple no sulfur bacterium *Rhodopseudomonas palustris*, commonly found in waste lagoons, in earthworm droppings, in marine coastal sediments and in ponds, can change its metabolism from photoheterotrophic to photoautotrophic, and from chemo-auto-trophic to chemo-hetero-trophic, depending on its adaptation needs[55,56].

In brief, microbial fuel cells electrical current-generating systems comprise an anode chamber and a cathode chamber separated by a membrane at ambient temperature and pressure. The microorganisms (e.g., *Rhodopseudomonas palustris)* are grown at the anode and convert the substrates into CO_2, protons, electrons, and other subatomic particles. The electrons transfer to the cathode via an external circuit that consists of a wire generating the electrical current. The separated protons pass through the membrane, driven by the electro-chemical gradient resulting from the high concentration of protons ions at the anode. Once at the cathode, protons and electrons react with oxygen to form water[55,56].

There are two general types of microbial fuel cells: those that require mediation, that is the initiation of the process by a chemical to transfer electrons from the microorganism; and those that occur spontaneously with no mediation needed because the microorganisms themselves have some type of electrochemically active redox proteins (i.e., cytochromes) on their outer envelope or membrane to start electron transfer.

While this particular set of solution are attractive for being efficient and self-contained natural net-zero carbon-neutral electricity-generating, and watered-producing systems, they are, at present, experimental and only laboratory-based. Theoretically, they could be small-scale units to supply clean energy for single-family homes, and even expanded in modular designs to serve large residential complexes, industry and residential neighborhoods. Practically however, at present environmentally safe scale-ups of such microbial cells still need to be engineered.

4. Conclusion

The evidence is incontrovertible that human activity in the last two hundred years—the Anthropocene Epoch of industrialization—has brought about a significant rise in greenhouse gases, which have led to entrapment of the planet's heat. Global warming has progressively altered ocean currents that are fundamentally in regulating the planet's climate. Global warming and climate change are ongoing threats to the preservation of our ecosystem and to the survival of every member of the vegetal and animal kingdoms, including the human species. It is timely and critical to address the multi-dimensional problems associated with climate change, and that we promptly find, evaluate and deploy effective solutions to blunt, block or even reverse the harming effects of greenhouse gasses.

Of particular concern is the thawing of polar caps, high altitude glaciers, and peri-glacial permafrost, and its consequence not only in the rising of sea levels, but in the release of novel and ancient pathogens that may be potentially harmful to human health, or even lethal. It is possible and even likely that nature-based solutions to these threats will be grounded in artificial intelligence (AI)-aided immune tweening[57] to include the development of new (5^{th}) generation multivalent polyfunctional comprehensive mRNA-based vaccines[58], multivalent antibiotics[59], and microRNA-based viral interference[60] interventions.

Alternatively, autologous immune enhancement therapy (AIET) protocols could be devised whereby naive T cells (e.g., CD3+CD8+, cytolytic T lymphocytes) could obtained from the patient's peripheral blood mononuclear cells following enrichment by dual-fluorescence flow cytometry. The cells would then be cultured, experimentally activated and led to mature *in vitro* as memory T cells cytolytic to endogenous cells infected by a newly identified permafrost virus for instance, and re-administered to the original donor, in a protocol similar to what is already deployed for chimeric antigen receptor-engineered T cells[61,62].

Conflict of interest

The authors declared no conflict of interest.

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