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Article

The Long-Term Survival of Human Civilization: A Science-Based Paradigm

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ABSTRACT

Recent studies of the likelihood of intelligent life in our galaxy suggest that we may be the only technological civilization. This imposes a profound responsibility on us to safeguard the resilient future of intelligence and technology in the galaxy. Therefore, ensuring that our civilization endures for millions of years is a prime scientific and moral priority. Our current influence on Earth's systems is undeniable, yet it remains superficial compared to the planet's long-term biogeodynamical evolution processes. By studying Earth's deep past and thinking on geological timescales, we can learn how to better navigate the deep future. At present, a guiding science-based paradigm for long-term survival of human civilization is missing and the research of the Earth-Life-Human system future focuses on relatively short-term timescales (decades, centuries). Here, we formulate the missing paradigm by presenting four core theses and studying their cultural, scientific and societal consequences. We begin with our motivation—that ours may be the only technologically advanced civilization in the galaxy and thus is precious. Next, we explore the greatest implication of our uniqueness—that we have a duty to ensure the long-term survival of our civilization, for the sake of the galaxy as well as our descendants. We then explore ways to do this, by consciously aligning civilization with solid Earth tempos and cycles. Finally, we propose "Future Dynamics"—a new interdisciplinary field focused on ensuring civilization's long-term survival by defining, modeling and quantifying potential future trajectories of the coupled Earth-Life-Human system over geological timescales.

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Research Highlights

- Human technological civilization is likely unique in the galaxy
- The long-term survival of our civilization is a prime scientific and moral priority
- Civilization's activities should be aligned with solid Earth tempos and cycles
- We propose "Future Dynamics"—a new scientific frontier focused on civilization's long-term survival

1. Introduction

Existential risks for and potential demise of human civilization are long-term foci of both scientific research and public discussions that have greatly intensified recently [1–4]. However, a guiding holistic paradigm for civilization long-term survival is missing and the research of the Earth-Life-Human system future focuses on relatively short-term timescales (decades, centuries). Below we formulate this paradigm by presenting four core theses to guide high-level science, education, policy and public discussions on the long-term survival of our civilization, emphasizing clarity, urgency, and scientific grounding. These begin with our motivation—that ours may be the only technologically advanced civilization in the galaxy and thus is precious. Next, we explore the greatest implication of our uniqueness—that we have a duty to ensure the long-term survival of our civilization, for the sake of the galaxy as well as our descendants. We then explore ways to do this, by consciously aligning civilization with solid Earth tempos and cycles. Finally, we propose "Future Dynamics"—a new interdisciplinary field focused on ensuring civilization's long-term survival by defining, modeling and quantifying the coupled biogeodynamical evolution of the Earth-Life-Human system over geological timescales.

2. Human Civilization Is Likely Alone in the Galaxy

If technological civilization on Earth is unique, preserving it becomes humanity's galactic responsibility. For decades we have scanned the skies for signals of other civilizations, with discouraging results. The Drake Equation (which estimates the number of communicative civilizations; [5]) suggests our galaxy could harbor many, but reality disagrees—a discrepancy known as the Fermi Paradox [6]. Recent research offers a compelling explanation: the specific astrophysical and planetary conditions needed for an advanced civilization to evolve may be exceedingly rare [7–9], even on planets with primitive life. The long evolution needed to evolve Active Communicating Civilizations (ACCs) may require very specific conditions for the evolution of complex life—especially coexisting continents, oceans, long-lived plate tectonics [8] and N_2-O_2-dominated atmospheres with minor amounts of CO_2 [9]. This rare combination is a product of a long-term planetary evolution [7–10]. Such planets likely make up less than 0.003–0.2% of all habitable worlds [8], which is in the strong contrast with the original optimistic estimate of 10–100% [11]. In other words, Earth might be a cosmic jackpot: a world where life not only emerged but advanced to intelligence and then technological prowess. These quantitative analyses are obviously limited by considering biogeodynamical conditions known for Earth. However, in the absence of any other known (extraterrestrial) technological civilization examples, these analyses should remain as the scientific basis for our self-consideration (up until the possibility of other potential evolution trajectories and biogeodynamical conditions will be discovered).

It should be noted that it is unsurprising that our brief and limited search for extraterrestrial civilizations has yielded no results. In practice, we have only examined small regions of nearby stars for a few decades. Ref. [12] estimated that our search of the cosmic "haystack" has covered only 10^{-19} of the relevant parameter space, while [13] suggest a modest improvement to 10^{-16}. Moreover, these efforts assume that advanced civilizations would transmit narrowband signals to maximize detectability [14], an assumption that may not hold universally. Finally, even under these assumptions, humanity has only had the technological means for interstellar signaling for a fleeting fraction of its existence. It is plausible that other civilizations exist but have not yet, or may never, develop the capability to broadcast across the galaxy. In addition, the assumption that other advanced civilizations want to communicate with us may be in question. Ref. [15] posited that one possible answer to the Fermi paradox is that advanced civilizations may well be aware of Earth but are merely watching us until we reach some more advanced state and therefore are radio-silent.

It is however important to realize that investigation and quantification of key biogeodynamical conditions needed for the emergence of intelligent technological life [7–9] remain essential as they provide boundary conditions for other plausible explanations of the Fermi Paradox. Therefore, recent additions to the requirements of intelligent technological life emergence from primitive life [8] may indeed imply that we are alone in the galaxy. In this case, Earth represents its intellectual and technological center (Figure 1), simply because no alternative perspective exists.

Figure 1. Galactic significance and responsibility of humans. Artist's conception of the Milky Way galaxy, our cosmic home, and Leonardo Da Vinci's Vitruvian Man. If intelligent life on Earth is unique, preserving it becomes a galactic responsibility.

3. Cultural Implications of Human Civilization Uniqueness

The possibility of human civilization uniqueness in the galaxy carries significant cultural implications. Since the Renaissance, modern thought has emphasized humanity's small place within an immense universe. Copernicus's heliocentric model began to unsettle the prevailing religious cosmology, and subsequent observations of Jupiter's moons, mountains on the Moon, and the great distance to the fixed stars reinforced Earth's lack of centrality. The resulting shift produced a civilizational vertigo with far-reaching philosophical, moral, and psychological consequences. Essentially, the Earth was no longer the center of the universe in any sense. And that implied that we humans may not be the chief concern of the Divine. Humanity was left to navigate its own course in a vast and indifferent cosmos, often adopting the view that ends justified means, however ruthless. In all the previous great religions, world history was a moral closet drama involving God(s) and humans, with Nature on Earth as the divine arena. Now humans were perhaps not the center of things and should look after ourselves, forming potent states to regulate human conduct, promoting rulers of those states ruthless enough to hold them together, and crushing any "barbarian" challengers to progress, adding their lands and resources to ours. For effective rule, the old pieties and traditions had to be crushed.

This unsettling perspective suggested that our civilization might also be a backwater in a vast variety of tribes; after all, throughout the renaissance we discovered hundreds of previously unknown cultures around the globe. The moral effects of that change in worldview were disturbing. In *King Lear*, Shakespeare gives voice to the profound disquiet of a society coming to terms with displacement from the cosmic center:

> "*These late eclipses in the sun and moon portend no good to us. Though the wisdom of nature can reason it thus and thus, yet nature finds itself scourged by the sequent effects. Love cools, friendship falls off, brothers divide; in cities, mutinies; in countries, discord; in palaces, treason; and the bond cracked 'twixt son and father. This villain of mine comes under the prediction: there's son against father. The King falls from bias of nature: there's father against child. We have seen the best of our time. Machinations, hollowness, treachery, and all ruinous disorders follow us disquietly to our graves*."

This literary unease coincided with historical transformations. The decline of a medieval worldview that placed humanity at the center was accompanied by the erosion of the idea of Earth as a sacred stage for Divine purpose. Five years after *King Lear* appeared, John Donne reflected on the same cultural rupture:

> "*And new philosophy calls all in doubt, The element of fire is quite put out, The sun is lost, and th'earth, and no man's wit Can well direct him where to look for it. And freely men confess that this world's spent, When in the planets and the firmament They seek so many new; they see that this Is crumbled out again to his atomies.'Tis all in pieces, all coherence gone, All just supply, and all relation; Prince, subject, father, son, are things forgot, For every man alone thinks he hath got. To be a phoenix, and that then can be None of that kind, of which he is, but he*."

Both poets recognized that a fundamental shift in worldview was also reshaping social relations. Within a decade, Machiavelli's *The Prince* was circulating in Europe, replacing older ideals of hierarchy and piety with a pragmatic politics of expedience and power.

Much more recently, science fiction has taken up the banner of "we're nothing special". The scientific justification for this began with Giovanni Schiaparelli's 1877 interpretation of linear features on Mars as "canali", which Camille Flammarion amplified on in the 1890's and Percival Lowell trumpeted from 1894 to his death in 1916 [16]. Lowell interpreted oases where large dark spots were observed from which several "canals" seemed to intersect, suggesting a water distribution system. On this flawed basis, Lowell deduced that Martians were mathematical, inventive, cosmopolitan, and technically superior to humans. Lowell opined: "Man is merely this Earth's highest production up to date. That he in any sense gauges the possibilities of the universe is humorous" [16]. The stimulus to human imagination was electrifying, spawning the Science Fiction industry. This began with a book entitled *The War of the Worlds* [17] and proliferated with technology including radio *War of the Worlds* (1938), many movies such as *It Came from Outer Space* (1953) and the *Star Wars* franchise (beginning 1977), and television shows such as *Star Trek* (1966). Books, movies, and videos on the many imagined advanced civilizations continue unabated today. The "Unidentified Flying Object" (UFO) phenomenon, which began in earnest after World War 2, still reverberates today, including continuing US Congressional hearings, is a predictable outcome of Lowell's over-interpretations.

Our worldview must therefore change again based on a science-driven approach. The imagined extraterrestrial civilizations of science fiction are unlikely to exist; instead, novelty and discovery must come from exploring our own galaxy and from the cultural and technological evolution of humanity itself. Exploring our galaxy and the human evolution that this might induce may now be the best way of experiencing cultural novelty and social innovation.

It would be a profound loss if the universe were not explored and understood through our sciences, arts, and imagination. This expansion of knowledge may itself represent a fundamental outcome of evolution, which over the last billion years has produced systems of interaction that gave rise to sensation, mental representations of the world, and thought. So, there is an upside to our new predicament: we can go on being explorers with a good conscience. And this time our explorations will not be at the cost of neighbors, as so many of our past explorations have been. And though advanced communicative life is unlikely elsewhere, the requirements for finding "Goldilocks" planets with primitive life by remote sensing seem to be common [8]. There are likely vast landscapes and unfamiliar environments awaiting exploration. There may be life which we may detect by analyzing exoplanet's atmospheres [18, 19]. And as pioneers move into other environments [20], they will surely form cultures and societies as bizarre as those of our own past. If we enjoy significantly more time to develop as a science-driven technological civilization, we will make our own strangenesses as we voyage onward from our cradle. We will adapt our bodies to different planetary environments (as did the Tibetan, Andean, and Ethiopian highlanders), but now with robotics and AI, and a richer and ever-growing knowledge of the potentials of our machines and ourselves.

What is the implication from the potential extreme rareness and even uniqueness of human intelligence in the universe for ourselves? It is to recognize that the stakes of human long-term survival are astronomically high. If our civilization fails, an entire galaxy could go quiet indefinitely. Conversely, if we endure and thrive, we preserve the only known spark of intelligent technological life in the Milky Way (Figure 1). This perspective impels us to begin shifting to a long-term, custodial mindset. Policies in areas from science and education to international and global cooperation should consider this overarching responsibility: we might be alone, and so the future of civilized life in the galaxy depends on us. Protecting and sustaining our civilization is not just a local or national concern, but a responsibility with galactic significance. In past societies, comparable responsibilities were often framed in religious or moral terms; today they can be understood as stewardship grounded in science and ethics.

4. Civilization's Long-Term Survival Is the Most Important Task

The longevity of our technological civilization must become a core priority for scientists, educators and decision-makers. All other ambitions, whether economic growth, social progress, or scientific discovery, ultimately hinge on civilization surviving and thriving in the long run. If we fail to navigate existential threats and sustainability challenges- both internal and external—those other goals become moot. As philosopher Nick Bostrom argued, reducing existential risk (the risk of civilization's destruction) "is strictly more important than any other global public good" [2]. In simpler terms: ensuring humanity's long-term survival unlocks all future possibilities, while fatal civilizational collapse forecloses them.

The new transdisciplinary field of Biogeodynamics [21–23] points the way. Biogeodynamics aims to investigate and quantify long-term interactions of Earth's interior with evolution of its surface, landscape, ocean, atmosphere, climate, biosphere and human civilization. It particularly aims to understand interactions between various components and subsystems of the complex Earth-Life system [22]. These components geosphere (solid Earth), hydrosphere (oceans, lakes, rivers), cryosphere (glaciers, ice sheets and sea ice), atmosphere (troposphere, stratosphere, ozone shield, ionosphere), magnetosphere (Earth's magnetic field and shield), critical zone (soils) and biosphere (life) along with the exosystem (Sun, bolides, cosmic radiation) and (geologically very recently) human civilization (Figure 2).

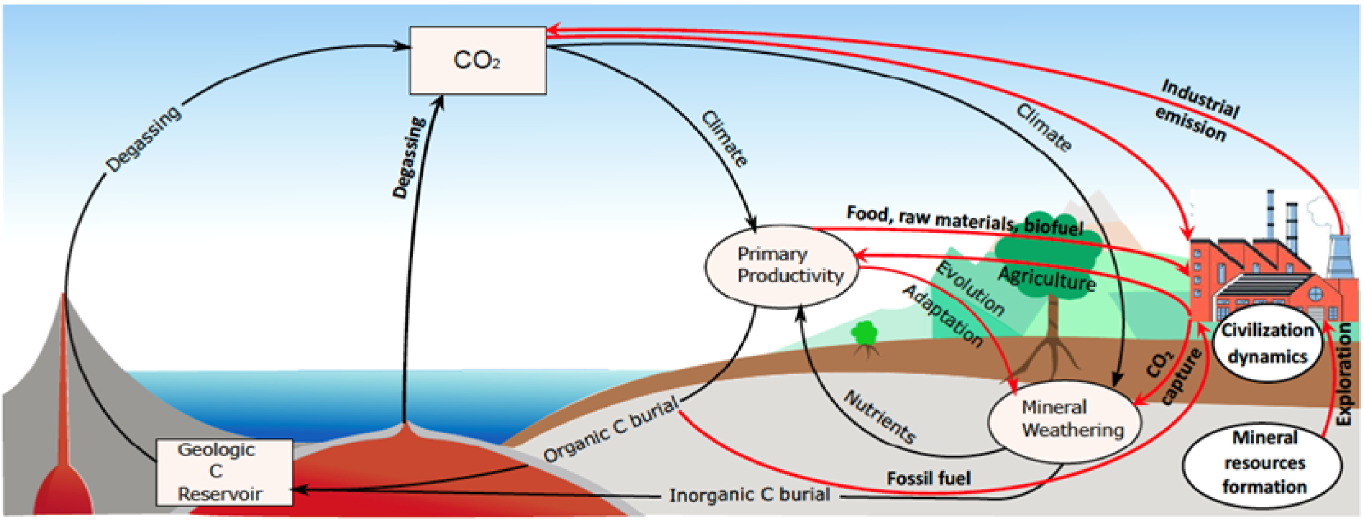

Figure 2. Biogeodynamical carbon cycle of the Earth-Life-Human system (modified after [24]). Red arrows show human civilization-related feedbacks to be explored on the long-term.

As civilization has undeniably become a surficial geological and biological power [25, 26] (Figures 2 and 3) it must start thinking, planning and acting on biogeodynamical timescales comparable to potential human biological longevity (0.2–8 Myr; [27]). Such extended longevity of our species is similar to the average longevity of complex terrestrial and marine species (1–11 Myr; [28–30]) including mammals (1–5 Myr; [31]). In fact, civilization makes it likely that further human evolution will be engineered, not accidental. Thinking on these timescales means planning for >1 million years of survival—a timeframe far beyond our usual planning horizons. This timescale dwarfs our imaginations, which at most can contemplate 10,000 years (https://longnow.org/clock/), about twice the length of recorded history. Why millions of years? Because in the grand scheme of Earth history, even the rise and fall of civilizations in a few centuries or millennia are mere blinks of an eye. Our own species, *Homo sapiens*, is young (ca. 0.2 Myr old; [27]), which poses a rather favorable condition for our potential future longevity.

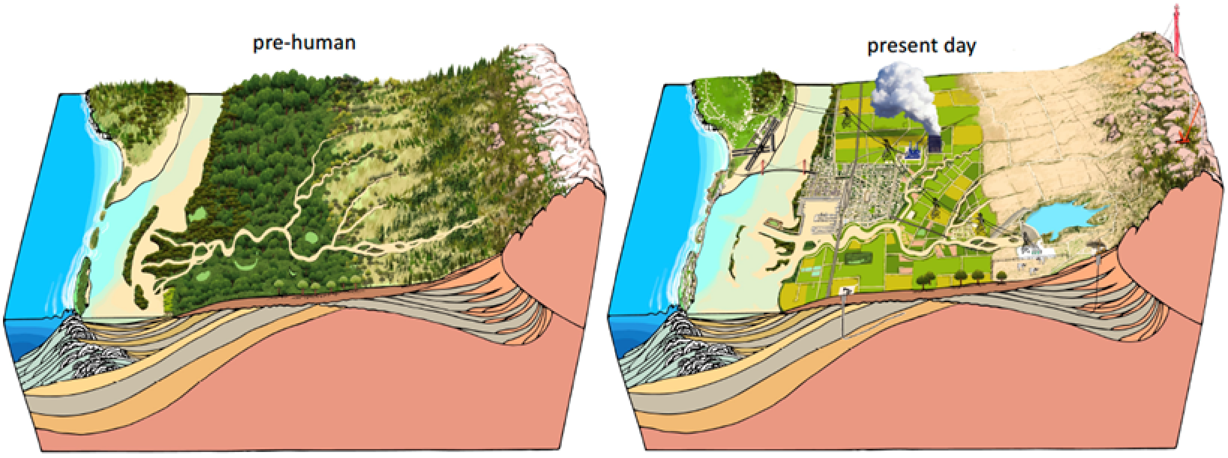

Figure 3. Effects of human civilization on the landscape and biosphere at continental margins. Despite undeniable major geological-biological influence of humans their effects remain surficial.

We must abandon the careless thinking that the long-term survival of human civilization is granted by the logic of our evolution and does not require any dedicated long-term global effort, perhaps because it is often assumed that emerging problems will be fixed by the next generations. It should be realized that the civilization survival is the greatest challenge as all intelligent organisms have a number of inherited behavior patterns (IBPs) [32, 33] that have high potential to induce civilization destruction [4]. IBPs have been evolutionarily tuned to optimize the survival and reproduction of organisms in their natural environments and may be incompatible with a civilized community [4]. In particular, the IBPs regulating energy harvesting and competition between tribes [34] may be inconsistent with the availability of corresponding technologies in a civilized community and are responsible for ecological crises and wars [4]. Similarly, our short-term planning as a consequence of trying to survive in civilization-free environments is surely incompatible with new challenges for global technological civilization long-term survival. To secure humanity's future, we must therefore begin to explore how to ensure our global technological society can ameliorate the negative effects of IBPsand navigate the slow but inexorable changes that occur on geological and biological timescales (from climate shifts to geographical changes and new biological species emergence). These events affect the surface Earth system where we live– the exosphere. At the same time, we must avoid the many self-inflicted IBP-related disasters including nuclear war, depletion of energy and mineral resources, and overpopulation, which lead to societal collapse [3]. Notably, if other communicative technological civilizations ever arose, their apparent absence today should warn us that their short longevity may be a common failure—perhaps through self-destruction or fatal environmental collapse.

Our scientific and societal challenge is to avoid repeating the apparent short lifespans of other potential civilizations, if they ever arose. By extending our planning horizon to millions of years, we encourage policies that favor long-term stability over short-term gains. For example:

- Global Catastrophic Risk Reduction: Prioritize preventing events that could end civilization (nuclear war, asteroid impacts, pandemics, uncontrolled artificial intelligence, etc.). Even "low-probability" risks become likely over mega-year spans, so they demand attention now.
- Sustainable Trajectory Design: Move beyond the idea of a sustainable steady state and aim for a sustainable time-dependent trajectory [2]—a scientifically navigated path of continuous adaptation and resilience that can carry us through changing global geographical, environmental, climatic and societal conditions. This includes developing technologies and social systems that can adaptively endure over tens of thou-

sands to millions of years.

- Future-oriented Institutions: Establish foresight units or think-tanks that explicitly consider scenarios on century to geological scales. Continue to gradually embed long-term metrics (such as for example already used in existing policies for the long-term safety of radioactive waste disposal sites) in governance (for instance, an "Earth legacy impact assessment" for major policies, evaluating effects on the deep future).

Embracing longevity as a mission brings a sense of urgency and optimism: urgency, because we know our current trajectory (e.g. resource depletion, climate change, population growth, wars) is unsustainable even on a scale of centuries; optimism, because with foresight based on the growing quantitative understanding of the Earth's long-term biogeodynamical evolution we can ensure that humanity flourishes for geological epochs. In practical terms, considering the next 10 million years as well as the next 10 years could begin to reframe policy decisions by taking the longevity aspect into routine consideration. This means investing in robust energy systems, planetary defense, conflict resolution mechanisms, IBPs-related risk mitigation, and figuring out how to spread life beyond Earth to create a multi-planet civilization serving as galactic insurance.

The key message is that civilization's far-future longevity is not a utopian topic—it is a necessary primary focus if we are to safeguard those innumerable generations yet to be born. And it should be recognized that this mission is feasible since we are already capable of creating material and cultural objects and knowledge that serve original and new roles over many generations: invention of the wheel and the use of fire, the poems of Homer and the laws of mathematics are well-known examples of this impressive longevity. It is unlikely that our IBPs-related short-term thinking habit will easily change and it may well be that it will take many generations for civilization to embrace our own long-term survival mission. In particular, scientists and educators will unlikely be able to change the existing short-sighted thinking of current generation of policy makers and the public. Therefore, the scientific and educational effort should focus on future generations by accumulating and broadcasting knowledge of potential conditions for the long-term survival of human civilization. New scientific knowledge will likely bring new societal opportunities and may thus result in respective societal paradigm changes.

5. Align Civilization Future with Earth's Deep Dynamics

Our only home is a dynamic planet with its own long-term cycles and understanding its past is key to ensuring our future. Human activity now rivals nature as an agent of change on the exosphere [25, 26], placing us in a new role as stewards of Earth's exosystem. Our industrial activities, from greenhouse gas emissions to deforestation and mass extinctions, are changing Earth's climate and biosphere on a global scale (Figures 2 and 3). Humans are causing an ongoing "Great Extinction" episode [35] and are likely delaying a new Ice Age. This realization has led some scientists to define the term Anthropocene for the current epoch—an era when human actions are a dominant driver of exospheric change [36]. However, our influence, powerful as it is, remains superficial compared to Earth's deeper geodynamical processes. We can pump CO_2 into the atmosphere and warm the climate, we can consume mineral resources, oil and gas, but the planet's deep interior carbon cycle and energy balance will ultimately shape the planet. Earth has several intrinsic controls (like vegetation-enhanced weathering of rocks that slowly absorbs CO_2, or volcanic outgassing that adds it back and the slow formation of various mineral deposits in subduction and continental collision zones and gradual assembling and maturation of hydrocarbon deposits at continental margins). These processes operate on timescales of thousands to millions of years and will outlast many human generations. To ensure our survival, we must align our civilization's activities and consumptions with these deeper Earth system dynamics, rather than against them. In contrast to humanity's strong impact on landscape, oceans and atmosphere, we have no discernible effect on the solid Earth system, including plate tectonics, mantle plumes and Earth's magnetic field. The surface changes will eventually propagate, and perhaps affect, mantle convection and plate tectonics in unpredictable ways but any effects such changes might have on the surface are far in the future.

The only way to better align the goal of humanity's long survival with Earth processes is by learning from the geological past, which holds vital lessons for the future of civilization. Our planet's rocks and fossils are records of past climates, catastrophes, and recoveries. For example, about 252 million years ago the Permian-Triassic mass extinction ("Great Dying") saw $>$80% of species wiped out, likely due to massive CO_2 emissions from eruption of the mantle plume-related Siberian Traps [37]. It takes millions of years for ecosystems to recover their diversity after global extinction events [38]. This characteristic pattern—rapid mass extinction and climate warming followed by an extremely slow (few million years) climate cooling and biological recovery—recurs in Earth's history and is intrinsic for the plants-mediated global biogeodynamical climate system of the last 390 million years, since trees and forests evolved [24, 39]. It tells us that if we drive our biosphere into collapse (through climate change, habitat destruction, etc.), the damage could last for geological timescales. Indeed, scientists warn that the biodiversity loss happening now could require at several million years for nature to rebound to prehuman levels [40]. Similar considerations may also apply to the climate recovery after prolonged anthropogenic release of greenhouse gasses [39]. In short, the actions we take in the next few centuries will imprint on the next several million years. That sobering fact urges to think more seriously about humanity's long-term future.

What does "aligning with Earth's dynamics" mean in practice? It means basing our policies on a sound understanding of Biogeodynamics and acting within the planetary boundaries that maintain long-term stability. For instance:

- Climate Action with Deep Time in Mind: We must limit atmospheric CO_2 to levels that avoid triggering feedback loops and passing irreversible climate tipping points [41, 42] we cannot control. The current climate crisis, if unchecked, could push Earth into a new steady state (e.g., a hothouse climate) likely to persist for millions of years [39]. Thus, developing robust Biogeodynamics-based long-term mitigation, restoration and adaptation strategies (like carbon removal, ecosystem regeneration and societal mitigation of long-term warming effects) are not just for immediate benefit but are an investment in the deep future. However, such efforts should not jeopardize economical and societal stability and thus civilization.
- Learning from Past Climate Crises: We need to study ancient events (such as ice ages, asteroid impacts, and past greenhouse episodes) and use this knowledge to better anticipate future changes. The deep past offers analogues for potential scenarios and clues to resilience. For example, understanding how Earth recovered from past high-CO_2 periods caused by extreme volcanism [39] can help guide us on steps needed to restore balance after our own carbon spike.
- Geoengineering Caution and Research: As we consider large-scale geoengineering (like CO_2 capture and/or reflecting sunlight to cool the planet), we must do so based on understanding Earth's complex climate history. Due to the strong non-linearity of the climate system [41, 42], quick technological "fixes" could have unintended consequences; a deep-time perspective teaches caution. We know, for instance, that Earth's coupled atmosphere-ocean-ice sheet dynamics has intrinsic climate tipping points, which may trigger abrupt changes in a climate already perturbed by anthropogenic activity and/or Milankovitch cycles [41, 43]. In this context, high impact-low likelihood events, both in the physical realm as well as in ecosystems, will be especially dangerous [43], so any intervention must be approached with extreme care based on both scientific knowledge and consensus.

Finally, aligning with Earth's dynamics also means respecting that nature has its own pace. While technology moves fast, ecological and geological processes are slow. We must moderate our demands on ecosystems (e.g., helping forests to regrow, species to migrate and adapt) as well as on mineral resources so that our civilization can co-evolve with both the deep Earth and the biosphere instead of crushing it [44]. By harmonizing our activities with intrinsic Earth's rhythms and biogeodynamical cycles (Figure 2)—for example, transitioning to renewable energy and reusing metals in a way that doesn't starve economies for energy or consumables, or planning cities mindful of sea-level and climate projections—humanity becomes more resilient. In essence, the deep past gives us a "user manual" for the planet. If we read it wisely, we can avoid repeating Earth's worst disasters and instead steer toward long-term habitability.

Learning from Past Civilizations Dynamics

Throughout history, complex societies have repeatedly emerged and dissolved, typically over spans of just a few centuries [3, 45, 46]. From Mesopotamia to Mesoamerica, and from imperial China to the Mediterranean empires, these cycles often involved phases of rapid growth, followed by stagnation, fragmentation, or abrupt collapse [47, 48]. This brevity contrasts sharply with the vastness of geological timescales, where significant shifts occur over hundreds of thousands or millions of years. A growing body of research suggests that the dynamics underlying civilizational lifecycles involve feedback between increasing social complexity, intensifying resource extraction, and declining returns on investment in institutions and infrastructure [49, 50]. These processes create inherent instabilities, especially as societies become increasingly locked into costly structures—whether bureaucratic, military, or symbolic [51]. Traditional explanations for collapse, from external invasions and natural disasters to class struggle and ecological destruction, have been complemented by more integrative frameworks that emphasize endogenous feedback loops and systemic fragility [52, 53]. Mathematical modeling of several past civilizations has shown that these feedbacks can replicate the rise and fall patterns observed in the archaeological record [54, 55]. Crucially, these findings indicate that collapse is not typically triggered by a single cause, but rather emerges from the interaction of many stressors operating over decades or centuries [3, 56]. Recognizing that complex societies operate within such constrained temporal windows forces a reevaluation of how modern civilization might extend its viability—not by denying these patterns, but by understanding and learning from them [57, 58].

Despite the short lifespans of past civilizations, it remains possible to extract meaningful insight at large spatial and temporal scales. Patterns of societal dynamics, though diverse in detail, often reveal regularities when viewed from a systems perspective [46, 54]. This opens the door to deliberate institutional design aimed at stability and resilience across centuries or even millennia

[44]. One of the paradoxes of complex societies is that the very forces that can lead to collapse, such as institutional inertia or the accumulation of sunk costs [59], can also, if properly directed, provide continuity and robustness. Institutions that evolve slowly tend to carry long memory and normative depth, allowing them to serve as stabilizing anchors in times of flux [60, 61]. Legal codes, governance structures, educational systems, and cultural narratives can embed long-term values and feedback constraints that resist the pull of short-term incentives [62]. Moreover, on planetary scales, certain forms of inertia—economic path dependence, infrastructure life-cycles, and large-scale resource commitments—can be leveraged to entrench beneficial trajectories, provided they are guided by foresight. The challenge lies in aligning these inertial forces with adaptive goals, such that policy becomes not merely reactive but anticipatory and generative. By embracing a multi-timescale mindset, where decisions are evaluated not only for their immediate impact but also for their influence on century or even epoch scale outcomes, modern civilization might achieve what previous ones could not: a sustainable trajectory that consciously transcends its own historical limits [63] (Figure 4).

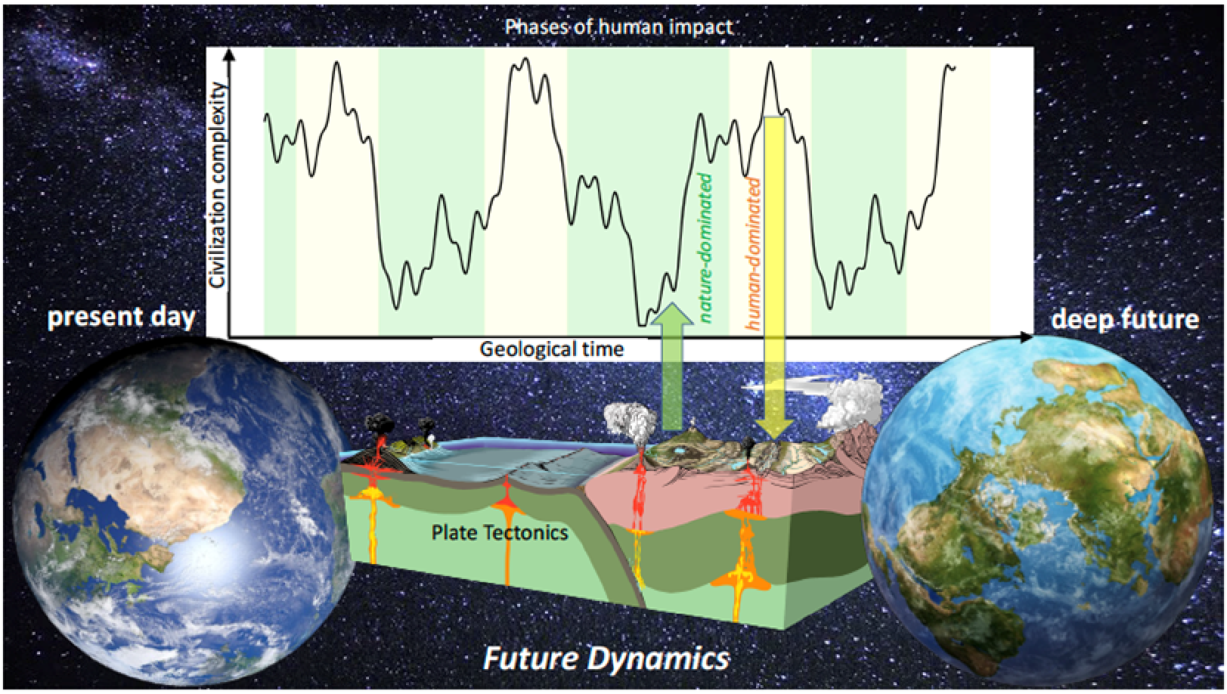

Figure 4. The concept of Future Dynamics bridging Earth's and human civilization's present day with their deep future by considering human civilization dynamics (top) under conditions of plate tectonics (bottom). The curve shows oscillations in civilizational complexity over time highlighting the alternating pattern of environmental impact across history. Yellow (human-dominated) regions mark periods of heightened human influence on Earth's systems, while green (nature-dominated) regions represent lower-impact phases.

The persistence of human stories across vast spans of time suggests that cultural memory can, under the right conditions, outlast even the civilizations that birthed it [64]. Some of humanity's oldest narratives, such as the myth of Orion and the Pleiades, may predate the migration out of Africa, implying transmission over tens of thousands of years through oral traditions [65]. Since the invention of writing, this capacity for durable memory has only grown. Texts like the Epic of Gilgamesh, composed more than four thousand years ago, or the philosophical works of ancient Greece and India, continue to inform human thought long after the political systems that produced them vanished [66]. Such artifacts demonstrate that symbolic communication—especially when preserved through writing, ritual, or monument -can transcend societal timescales. In the modern era, globalization and digital technology offer an unprecedented opportunity to seed cultural messages with similarly enduring potential [67]. By deliberately crafting narratives, scientific principles, or ethical frameworks intended for long-term transmission, contemporary civilization can create intellectual, technological and moral legacies that persist independently of political continuity. While the material conditions of society may fluctuate, the informational content embedded in durable formats—whether etched in stone, stored in robust digital media, or encoded into institutional practice—can carry forward foundational lessons [68, 69]. This offers a profound form of continuity: not the survival of a particular state or economy, but the preservation of values, knowledge, warnings, and aspirations that can inform distant descendants or successor societies [2].

Modern civilization represents a fundamental shift in the trajectory of Earth system dynamics [36] (Figures 2 and 3). For most of planetary history, the biosphere and geosphere evolved in a "nature phase," where natural processes such as volcanism, orbital cycles, and biological evolution dominated, with minimal feedback from any single species [25, 70] (Figure 4). Human societies, until recently, remained largely embedded within this framework, constrained by environmental rhythms and unable to exert more than local or regional influence on planetary systems. That equilibrium has now been disrupted [71]. The accumulation of scientific knowledge and the exploitation of concentrated energy reserves, particularly fossil fuels, have enabled humanity to transition into a "human phase" of biogeodynamical evolution—an unprecedented condition where anthropogenic activities begin to reshape planetary systems at scale and pace previously reserved for geological or astronomical forces [26] (Figures 2 and 4). Industrial emissions are altering atmospheric composition, land use change is transforming biomes, and technological networks now mediate the flows of matter and information across the globe [44]. These transformations are not merely superficial; they are initiating long-range biogeodynamical feedbacks that could alter climate regimes, ocean chemistry, and biospheric stability for tens of thousands of years or more [39]. This new phase presents a dual reality: immense power paired with immense responsibility (Figures 1, 2 and 4). While earlier societies interacted with nature largely as passive recipients, modern civilization must grapple with its role as an active, system-level agent, capable of triggering transformations on par with natural catastrophes—or, conversely, of stabilizing Earth systems through informed restraint [43] (Figures 2 and 4).

Taken together, these insights paint a nuanced picture of civilizational time (Figure 4). While the rise and fall of societies unfold over spans much shorter than geological or evolutionary timescales, the cumulative effects of human activity (if properly implemented through the global civilization legacies) can persist far longer, leaving indelible traces on the Earth system. Figure 4 illustrates how human impact may unfold in alternating phases while preserving civilization sustainability through the deep future: periods of high complexity and influence, where environmental feedbacks intensify, followed by intervals of lower impact, marked by reduced complexity or systemic reorganization. These fluctuations are likely to continue into the future, reflecting both the resilience and vulnerability of global civilization. Crucially, this pattern does not imply inevitability or futility, but rather the need for conscious stewardship. Even in the face of civilizational turnover, it is possible to carry forward core messages, values, and technical and scientific knowledge. This will ensure that these critical insights will not be lost with the vanishing societal structures that once created and housed them [64, 67, 69]. As the result, continuity will be preserved for the progressive long-term accumulation of the global scientific, technological and societal knowledge. By learning to operate within planetary boundaries during phases of high impact and investing in durable, intergenerational forms of memory and governance, humanity can avoid the most destructive dynamics and maintain continuity even amid change. Ultimately, long-term survival hinges not on avoiding change, but on managing it—minimizing irreversible damage during peaks of activity and preparing robust legacies that can be reactivated or reinterpreted in the quieter stretches between [2]. The deep future, like the deep past, will likely contain waves of complexity and calm (e.g., [24, 39]); the task before us is to shape those waves wisely (Figure 4).

6. Pioneering Future Dynamics

To tackle these unprecedented challenges, we propose a new scientific frontier for studying Earth–Life–Human futures. We can call it "Future Dynamics"—a transdisciplinary field focused on understanding, modeling and quantifying the coupled biogeodynamical evolution of the Earth-Life-Human system over geological timescales (Figure 4). We already have specialists in geodynamics, landscape evolution, climate science, ecology, and social sciences, but lack an integrated framework tying these expert communities together to help prepare for the future. Comprehensive models that entangle human and biogeodynamical processes are not available and need to be developed. In other words, although we routinely model the climate up to 2100 [63] or project population and economic growth for a few decades [72], no existing model can simulate what happens if we, say, double atmospheric CO_2 and then maintain a technological society for 10,000+ years. We have increasingly robust models for geodynamics and biogeodynamics which help us understand Earth's coupled tectonic, surface, landscape, climate and biosphere evolution [24, 73–76]—now we need quantitative models for potential future biogeodynamical evolution trajectories. These models are already starting to emerge [77–79].

What would Future Dynamics involve? At its core, it would focus on computational modelling joining the knowledge of Earth's past with forward-looking scenarios for Earth's future. This requires big-picture, systems thinking involving an unusually large range of disciplines:

- Coupling Human and Earth-Life Systems: Future Dynamics would develop models that include geological forces (like volcanism and tectonics), biological evolution, climate change, and human factors (technology, economics, policy). For example, how might the formation of a supercontinent 200 million years from

now [77, 78] affect what goes on at the surface, from national boundaries to climate? Such ambitious questions force us to identify the fundamental principles governing long-term Earth–Life-Human interactions.
- Long-Term Experiments and Scenarios: just as we run climate models under different emission scenarios for 2100, Future Dynamicists could run scenarios for the next 1,000,000 years or longer [77, 78]. These could explore, for instance, the outcome of various strategies: one scenario might assume humanity quickly transitions to sustainable energy and stabilizes climate, another might examine slow action and feedback effects over millennia. The goal would not be to predict the far future but to map the possibilities and identify which potential global trajectories lead to survival vs. collapse.
- Insights for Policy Today: While 10 million years is far beyond any policy timeframe, studying it can yield insights actionable now. Future Dynamics can highlight which variables matter most for long-term outcomes. It may show tipping points to avoid (e.g., the extent of species loss that irreversibly damages critical biosphere feedbacks) and "safe operating spaces" to aim for (e.g., maintaining climate within a range that avoids both frozen and runaway greenhouse states; [80]). It can also inform sustainability as a trajectory rather than a fixed end-state [2], emphasizing adaptability and learning as conditions change.

In particular, for climate change, the following hierarchical approach can be suggested on the basis of four characteristic biogeodynamical and societal timescales:

- Geological time scale goals (millions of years) - moderation of and adaptation to climate effects of plate motions and related geographical, environmental and volcanic degassing changes.
- Long-term goals (10,000–100,000 years)—moderation of and adaptation to climate effects of the Milancovich cycles.
- Intermediate-term goals (100–10,000 years) - moderation of and adaptation to climate effects of global societal evolutionary changes, e.g., related to variations between "human-dominated" and "nature-dominated" phases (Figure 4).
- Short-term goals ($<$100 years)—moderation of and adaptation to climate effects of short-term anthropogenic changes related to global technological, agricultural and population changes.

Similar hierarchical approaches can be developed for other relevant societal and environmental processes, which are obviously all interrelated (Figure 2).

Establishing Future Dynamics as a field will require investment, imagination and education. We will need to bring together geologists, biologists, climate modelers, futurists, and social scientists into collaborative teams. Science fiction writers and film producers will have important roles to play. Education and funding structures may need to adapt—traditionally, geophysicists and sociologists have little overlap, but Future Dynamics requires developing a common glossary and some sharing and combining of tools and data. The payoff could be immense. By moving towards a rigorous understanding of coupled Earth–Life–Human systems, we could empower civilization to anticipate and shape the distant future (Figure 4), rather than stumble into it blindly and fearfully. This new science could be coordinated on international and even global levels—for example, a "Future Dynamics Council" or research programs that work similarly to how the IPCC (Intergovernmental Panel on Climate Change) operates, but with a mandate for inquiry extending to very long-term risks and opportunities. Such an effort would continuously update humanity's far-future outlook based on the latest science. A sustained educational effort to build a holistic understanding of coupled Earth–Life–Human systems in the society would be important for achieving global coherency and optimism.

This effort should matter to policymakers. Policymakers are accustomed to reacting to immediate issues, but the concept of Future Dynamics urges a shift toward proactive long-range planning (e.g., for nuclear waste disposal; [81]; CO_2 sequestration; [82]; and agricultural activities; [83, 84]). Decisions made today (on energy infrastructure, biodiversity protection, climate policy etc.; [85]) set us on trajectories, some of which will play out over millions of years. By consulting the best science on these trajectories, leaders can choose paths likely keep future options open. For example, preserving tropical rainforests today might be a short-term climate mitigation strategy; in the long term it could help ensure that future Earth still has a stable climate and rich ecology that our distant descendants (or other evolved creatures) will depend on. Future Dynamics provides the knowledge base to justify and guide such foresighted policies. In sum, we need to institutionalize long-term thinking by putting it on a sound scientific basis. Just as our ancestors benefited from our planet's stable environment over 10,000 years of Holocene climate (which allowed agriculture and civilization to flourish; [71]), we must now act to maintain a stable, livable planet and sustainable, adaptive civilization trajectory [2] to the future inhabitants of Earth for as far in the future as possible.

7. Conclusions

In presenting this new paradigm for human civilization long-term survival, the aim is to engage the scientific community to provide educators, decision-makers and public with a bold vision that is grounded in science. Humanity is likely unique in the galaxy—a fact that bestows both an honor and a burden on us to safeguard civilization and its potentials. Our central priority should be to ensure that human civilization remains viable over the long term, maintaining continuity of knowledge, technology, and planetary stewardship into the deep future, so that we can continue to explore and hopefully colonize the galaxy. Achieving these demands aligning our society with the powerful engines of Earth's biogeodynamical system, learning from the past, and committing to a path of sustainable longevity and continued progress of knowledge and technology. It also calls for innovation in how we think, learn and plan—embracing a new Future Dynamics perspective that transcends short-term political considerations. Policymakers today have the opportunity to be true architects of the future: to lay the foundation for a resilient civilization that is optimized to weather the ages. In doing so, we fulfill a responsibility not just to our children or grandchildren, but to the entire chain of life and consciousness that hopefully will emanate from our actions, stretching millions of years ahead (Figure 4). The long-term survival of human civilization is the bedrock upon which all other aspirations rest—and it is a mission worthy of our greatest efforts.

Author Contributions

T.V.G.: Funding acquisition; Formulation of the four core theses; Writing and editing the paper. R.G.S.: Funding acquisition; Writing and editing the paper. F.T.: Writing and editing the paper. S.R.: Writing and editing the paper. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Chat GPT Deep research to produce the initial paper outline.

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