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Pancosmorio (world limit) theory of the sustainability of human migration and settlement in space

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It seems to be an accepted assumption that human migration into space is inevitable. However, almost 60 years of scientific studies of the effects of space on Earth life suggest this is not a given. Life on Earth evolved in the context of conditions that are unique to Earth and are not duplicated anywhere else in our solar system. The science indicates that life-sustaining conditions on Earth could be the very things that inhibit our ability to live off-Earth. This paper combines 100 years of scientific development of a theory of ecological thermodynamics with classical mechanics theory and analytical models of *self-restoring* heat engines to explain how the Sun and Earth have evolved into islands of order in the entropy of space. An explanation is provided regarding how naturally occurring conservative force fields engage a diversity of natural resources in *semi-reversible* cycles that build a high-exergy ecosphere. The science infers that the ability to establish a human settlement in space without Earth-like *self-restoring order*, *capacity*, and *organization* will result in settlement sustainment challenges. Historical evidence of Earth settlements with disrupted ecosystems point to the following possibilities. Supply chains would disappear, market resources would be depleted, advancement in human pursuits would be disrupted, social and governance systems would falter or collapse, human population numbers would decline, genetic diversity in the human genome would be lost, average human individual biomass would decrease, and human knowledge and understanding would be forgotten. What does it mean to have a location in space outside of Earth be "like Earth?" The results of research are presented as a *pancosmorio theory of human sustainability* that is developed using the scientific philosophy methodology of abductive reasoning. Four analytical models of space ecosphere sustainability and five hypotheses with proposed tests for falsifiability are provided, including a theorem that suggests a limit to human expansion into space. A new *quantitative method of human sustainability* is developed from theories of network ecology, providing orthogonal properties of an ecosystem network stability function based upon an ecosystem network production function. Conclusions are made regarding the potential for sustainable development in space using balanced sustainability. Insights are provided regarding human endeavors on the Moon and Mars, as well as the Fermi paradox.

KEYWORDS

sustainability, resilience, terraform, sustainable development, ecology, thermodynamics, space habitation, Fermi paradox

1 Introduction

It seems to be an accepted assumption that human migration into space is inevitable. Is this a valid assumption? Is it based on facts, or is it based upon a belief in human exceptionalism? Humans are migrators. The evidence is clear: humans are spread across Earth. Is there something about humans that would suggest that migrating into space is not much different than migrating out of Africa into Eurasia?

Humans are a species of Earth. We are connected to Earth through evolution. However, we are also connected to space through evolution. We are made of heavy elements generated by fusion in the cores of stars. We are warmed by the radiation of the closest star to us, the Sun. We exist because that star formed into a ball of fusing hydrogen in the local space under the influence of the gravitational force and the nuclear strong force, and because nearby star dust formed into a planet, Earth. Is it unreasonable to assume that human life had as part of its causal chain the formation of a star and a planet? The counterexample of Earth life evolving into existence without an actual Earth and without the power of the Sun suggests the stated assumption is a plausible initial causation.

What does the evolutionary connection of humans to a star and a planet mean for their ability to inhabit space? If human life is existentially dependent upon Earth, then we hypothesize that any human enterprise attempting to establish itself in space outside of Earth without an equivalent system will be unsustainable. We present a new theory and the supporting scientific research that human sustainability in space depends upon conditions that have been evolutionarily established within the Earth ecosphere[1] by universal law.

To open the presented theory, the tools of analysis and abductive reasoning will be astrophysics initially, classical physics more broadly, and the burgeoning science of ecological thermodynamics theory (Nielsen et al., 2020). The proof begins with a cosmological review of the evolution of Earth and the Sun into islands of order in the entropy of an expanding space. All life evolved within the context of this order and a collection of evolving conditions. The sustainment of human life is dependent upon the sustainment of this order with its conditions. The level of detail provided in this Introduction section is to assist with understanding how materials acted on by conservative forces are captured in *semi-reversible* cycles that utilize energy from the Sun to build *dissipative structures* in the form of *self-restoring* heat engines. This will be contrasted with human-designed, technological systems that attempt to perform the same functions using non-self-restoring means. The objective is to understand what is required for sustainable human habitation in space. What will be revealed is that *human sustainability* is about more than just diversity and energy efficiency; it is about *self-restoring order*, *capacity*, and *organization*.

1.1 Self-restoring heat engines provide a basis for sustainable growth

The basis condition of the ecosphere from which all life evolves is the existence of Earth and the Sun. Earth and the Sun form because of the conservative gravitational and nuclear strong forces that are universal laws described by physics theory. They are conservative in that the energy contained by the interaction between properties of matter and the fields of these forces is conserved. No irreversible entropy is generated by the interaction of conservative force fields and matter. The gravitational force results in particles of matter being pulled together through inelastic collisions into collections of greater density to form Earth and the Sun. The nuclear strong force results in atoms of hydrogen being pulled together through inelastic collisions to fuse into helium within the Sun as it collapses under the gravitational force. Calculations of the changes in entropy of the matter that collapses from a cloud of hydrogen to form the Sun and the matter that collapses from a debris field of heavier elements to form Earth reveal that the collapsing matter has a net negative change in entropy.[2] As the matter collapses, the heat that is generated and expelled from Earth and the Sun spreads into space and results in a larger net positive change in entropy in the surrounding space than the net negative change in entropy of the matter that forms Earth and the Sun into relative islands of order, thus not violating the second law of thermodynamics (Wallace, 2010; de Souza et al., 2015; Greene, 2021, page 63 and footnote 14).

The generation of heat and the net positive change in entropy correlates with the conservation of momentum theorem that dictates that when inelastic collisions occur, mechanical energy that is typically conserved in the interactions between matter and the conservative gravitational and nuclear strong force fields is lost to heat-generating mechanisms in a proportion that conserves the momentum of matter (see Supplementary Presentation 1: *Pancosmorio Theory Classical Mechanics Clarifications* for discussion of Conservation of Momentum and Entropy). If the process ends here, the result is the Sun at a high temperature, the Earth at a lower temperature, and surrounding space at an even lower temperature, with heat passing from the Sun to Earth and space and from Earth to space. This simplest form of the movement of energy in the form of heat from a high temperature source to a low temperature sink produces maximum specific entropy[3] (Figure 1A).

However, the process does not end there. The result of the formation of Earth is a gravity well. This gravity well has a spherical rock lithosphere and core at its center with a hydrosphere of water and an atmosphere of gases pulled against it. The force of gravity pulling against the water and gases results in normal forces of the lithosphere pushing back against the hydrosphere and atmosphere; these normal forces fundamentally exist because of the conservative electrical force of repulsion between atoms that exceeds the force of the gravitational field packing the atoms together. It is the pull of gravity and the push of such

1 This paper uses the term "ecosphere" instead of the commonly used term "biosphere." "Ecosphere" is defined by the Collins English Dictionary (Ecosphere, 2023) as "the planetary ecosystem, including all the earth's living organisms and their physical environment." It relates to the study of ecology as compared to the study of biology. Biology is the study of life, whereas ecology is the study of how life interacts with its physical environment. Use of the term "biosphere" will be limited to the sum of all biotic organisms of an ecosphere.

2 The major contributions to the net negative entropy change are that the atoms take up less space and form into new atoms that are fewer in number.

3 "Specific entropy" is the amount of entropy generated per unit mass. Speaking in terms of specific entropy allows for comparison of the varying states of an open system that might increase or decrease in quantity of matter over time, the open system in this case being Earth.

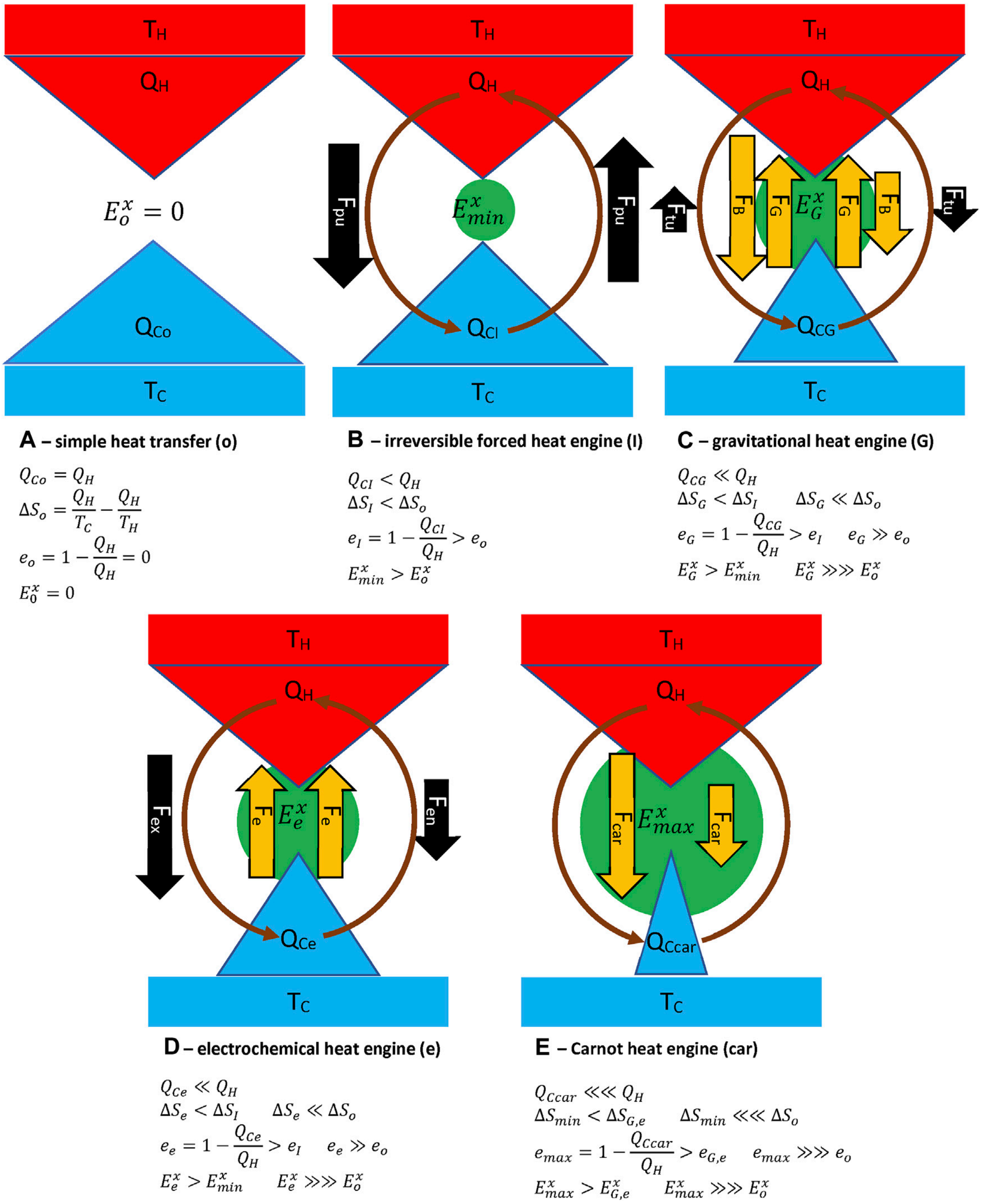

FIGURE 1
Heat engine exergy diagrams indicate useful work in the form of exergy buildup. They are arranged in order (**(A)** through **(E)**) of increasing exergy, decreasing heat loss to the heat sink, and decreasing specific entropy and net (universal) entropy generation. They present ecological thermodynamic parameters in terms of a heat reservoir (red rectangle, top, at temperature T_H), a heat sink (blue rectangle, bottom, at temperature T_C), heat transfer into material out of a heat reservoir (red triangles, with heat input Q_H), heat transfer out of material into a heat sink (blue triangles, with heat output Q_C) material displacement captured in heat engine cycles (brown counterclockwise circle arrows), and exergy (green circles). Larger bases of triangles indicate greater heat transfer. Larger circles indicate greater exergy. Gold force arrows inside of material displacement circle are conservative forces and do not generate additional heat; F_G is gravity, F_B is buoyancy (see Supplementary Presentation 1: *Pancosmorio Theory Classical Mechanics Clarifications* for discussion of Buoyancy as a Conservative Force), F_e is electrical/electrochemical, and F_{car} is the adiabatic and isothermal expansion and contraction of an ideal gas of a theoretical Carnot cycle. Black force arrows outside of material displacement circle are non-conservative forces due to inelastic collisions and increase heat output; F_{pu} is pumping force, F_{tu} is air friction/turbulence, F_{ex} is exothermic/debonding explosive force, and F_{en} is endothermic/bonding collision force. Relative directions of force arrows align with relative directions of material displacement circle, force arrows left of center matching to material displacement toward the heat release portion of the cycle and force arrows right of center matching to material displacement toward the heat absorption part of the cycle. Longer arrows indicate greater force, being additive according to Newton's Second Law with the sum either supporting or resisting the momentum of material displacement.

normal forces that result in the phenomenon of the apparent force known as weight (see Supplementary Presentation 1: *Pancosmorio Theory Classical Mechanics Clarifications* for discussion of The Apparent Force of Weight).

Weight resulting from the combination of gravity and normal forces produces an important effect. The weight of layers of water and atmosphere piled from the lithosphere to the top of the hydrosphere and atmosphere result in a gradient of depth pressures, with depths closer to the lithosphere having greater pressures. These material spheres, their depth pressures, and the solar insolation falling on the interfaces between the material spheres result in convective forces driven by temperature differences and in the latent heat of evaporation of water from the hydrosphere. Solar power is used to overcome gravity through the gravitationally driven conservative buoyancy force lifting masses of air and evaporated water through the pressure gradient and higher into the atmosphere (see Supplementary Presentation 1: *Pancosmorio Theory Classical Mechanics Clarifications* for discussion of Buoyancy as a Conservative Force). Gravitational potential energy of the rising air and water vapor increase, such that when the air and water vapor expel heat in the upper atmosphere (and positive specific entropy) into space, the gravitational potential energy generates the power to return each unit of mass to its elevation of origin.

The solar insolation and gravity power sources, the air pressure gradient, and the conservative gravitational and buoyant forces result in a gravitational heat engine (Figure 1C) that drives the rising and falling actions to produce the orderly *gravitational dissipative structures* of the water cycle and barometric weather cells. Forming the material trapped in the gravity well of Earth into the orderly structures of heat engines results in the material having another net negative specific entropy change. This moves Earth further away from thermodynamic equilibrium. However, the orderly structures are also *dissipative structures* in that they move heat through the Earth ecosphere and out into space. If the gravitational heat engines only involved an ideal gas atmosphere as a working medium, then the net change in the entropy of the heat captured from solar insolation and then expelled to the space heat sink would be zero, as with a Carnot cycle (Figure 1E). However, considering the atmosphere is not an ideal gas, there are inelastic collisions (i.e., friction) occurring between particles as gravitational potential energy converts to kinetic energy, and kinetic energy is subsequently lost to heat through the conservation of momentum in inelastic collisions. This inefficiency steals some of the heat input from solar insolation away from performing useful work, resulting in the generation of extra heat that is lost to space. It is this extra heat loss that results in a net positive entropy change for the heat transfer of solar heat passing through the material of Earth and out into space that adds up over time and exceeds the net negative change of entropy for the material formed into orderly *dissipative structures* on Earth. There is a total positive change in entropy for the overall Sun-Earth-space system.

We conceive that the conservative gravitational field acts as an *ideal pump* (Figure 2A) that neither depletes an external energy source nor generates entropy with its pumping action that uses a conservative force. We postulate that the action of the *ideal pump* of the gravitational heat engine results in a *semi-reversible* cycle. In effect, this means that the gravitational heat engine is *self-restoring* even as the working medium used by the heat engine loses kinetic energy to heat during non-conservative inelastic collisions between the non-ideal-gas particles of the atmosphere.

As time passes, Earth becomes dominated by geophysical and biogeochemical cycles capturing available resources into *gravitational* and *electrochemical dissipative structures* that are more orderly and result in a net negative specific entropy change for Earth, moving it further from thermodynamic equilibrium. Electrochemical interactions require proximity of constituents and availability of heat, so the development of electrochemical heat engines proceeds and grows as the right combinations of elements and molecules are brought together by the geophysical cycles involving gravity, water, weather, and heat from solar and geothermal power. We postulate that electrochemical heat engines are pairs of irreversible endothermic and exothermic chemical reactions that sustain each other in a *semi-reversible* cycle (Figure 1D) with the conservative electrical force acting as an *ideal pump*. The irreversibility of the chemical reactions is referring to the heat that is required to initiate the reactions and the mechanical energy that is lost to inelastic collisions when atoms are kinetically pulled together (i.e., chemically bonded) or kinetically separated (i.e., bond breaking). Whereas an endothermic chemical reaction combines various atoms and molecules into a larger molecule, an exothermic chemical reaction breaks that larger molecule back down into the original atoms and molecules, thus making

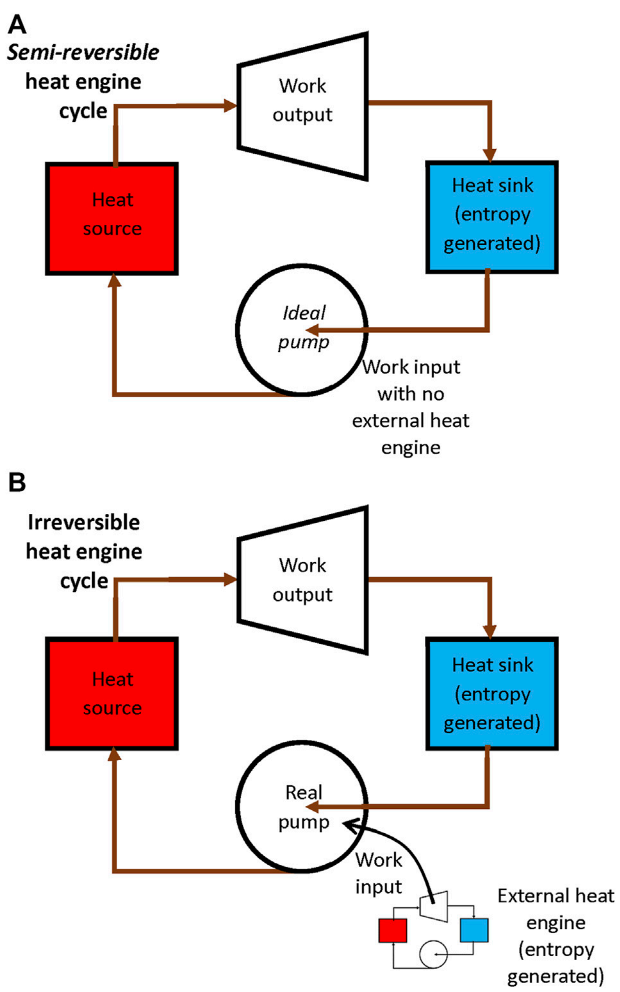

FIGURE 2
Comparison of two heat engine cycles. **(A)** The *semi-reversible* heat engine cycle has an *ideal pump* in the form of a conservative force that requires no external heat engine, and therefore requires no maintenance and never fails. **(B)** The irreversible heat engine cycle requires an external heat engine to drive the real pump, requires maintenance due to wear and tear, and suffers from ultimate failure.

TABLE 1 Universe as an isolated system containing Earth as a subsystem under full solar insolation.

Universe as an isolated system containing earth as a subsystem under full solar insolation
An analytical model formulation using the first and second laws of thermodynamics for the idealized case of the universe as an isolated system containing an ecosphere (e.g., Earth) as a subsystem under full solar insolation is provided in Eq. 1.[a] $$dW_u \leq -d\left(U^x - T_o S + p_o V - \sum \mu_{io} N_i\right) \quad (1)$$ In this case, the useful work (W_u) that is performed by the ecosphere under solar insolation is less than or equal to the negative change in exergy of the ecosphere (Mejer and Jørgensen, 1979; Jørgensen and Mejer, 1981; Schneider and Kay, 1994). "Exergy" (E^x), Eq. 2, is defined as "the amount of useful work energy the ecosphere can perform when utilizing all of its resources to come into thermodynamic equilibrium[b] with the reference state reservoir (subscript o) comprised of solar insolation, the surrounding space, and the initially formed Earth as an inorganic soup of chemicals" (Eriksson et al., 1976; Jørgensen, 2002, pp. 131–133). The resources that are included in exergy are energy and fuel for all heat engines that conservatively and non-conservatively convert energy and matter (Schrödinger, 1944; Eriksson et al., 1976; Jørgensen, 2002, p. 131). $$E^x \equiv U^x - T_o S + p_o V - \sum \mu_{io} N_i \quad (2)$$ The terms of exergy include available work energy built up in the ecosphere (U^x) minus the reference case of the initial formation of the ecosphere and the entropy of heat loss to space ($T_o S$, the product of the temperature of the space reservoir T_o and entropy of the ecosphere S), the work done expanding against the surrounding space ($p_o V$, the product of the pressure of the space reservoir p_o and the volume of the ecosphere V), and the chemical energy of the initially available chemicals in the inorganic soup ($\sum \mu_{io} N_i$, the sum of the products of the molecular chemical energies μ_{io} and the mole quantities of all available chemicals N_i). The total available work energy contained in the ecosphere following build-up (U^x), Eq. 3, is a result of the final value of entropy of heat loss to space ($T_f S$), the final work done expanding against the surrounding space ($p_f V$), and the final chemical energy built up in the ecosphere ($\sum \mu_{if} N_i$) (Jørgensen, 2002, pp. 131–135). $$U^x = T_f S - p_f V + \sum \mu_{if} N_i \quad (3)$$ U^x, S, V, and N_i are extensive state variables of the ecosphere that can be increased by the engagement of more material and energy in *semi-reversible* conservative-force cycles. When the average states of all *semi-reversible* cycles for all matter on Earth are summed up at any given moment, the value at that moment of summations of total exergy and available work energy are positive. This is equivalent to saying that there is, on average, an increase in net negative entropy change on Earth. This has been validated by measurements in nature (Aoki, 1988). The first and second laws of thermodynamics result in an increase in order on Earth in the form of exergy containing heat engine cycles with total entropy of the universe still increasing (Layzer, 1988; Jørgensen et al., 1998).

[a]This equation has been derived specifically to consider the useful work that can be performed by the biochemistry of an ecosphere. It does not include geophysical cycles. A complete consideration of conservation of energy would include all components of energy.
[b]Thermodynamic equilibrium is the state of total homogeneity and maximal disorder. This equates to maximum entropy. In this state, no further work can be done. This is also known in the scientific vernacular as "heat death."

that material re-available for the recurrence of the endothermic chemical reaction and the *semi-reversible* cycle. The electric field is conserved in this cycle, with its full energy continuing to be available to govern the cycle, just as with the gravitational field.

Defining gravitational heat engine cycles and electrochemical heat engine cycles as being *semi-reversible* is to differentiate them from both a completely reversible ideal Carnot cycle (Figure 1E) and a completely irreversible heat engine cycle in which all applied forces are non-conservative (Figure 1B). The implication of the first and second laws of thermodynamics is that naturally occurring *self-restoring* heat engines are more efficient than irreversible forced heat engines, resulting in a *semi-reversible* cycle that generates the entropy of heat transfer at a lower rate than an irreversible cycle relative to equivalent useful work performance. *Self-restoring* heat engines utilize *ideal pumps*, described earlier. They do not require an external heat engine to drive them as is required by the pump of an irreversible heat engine cycle (Figure 2B). They also do not require maintenance due to wear, nor do they suffer from ultimate failure. The irreversible heat engine's pumping force, the pump external power source, and the pump's wear and failure are more entropic than the *semi-reversible* cycles of *self-restoring* heat engines.

The transition away from thermodynamic equilibrium is explained in Table 1 as an exergy-building process of the Universe. As entropy generation rate of the solar heat transfer through the material of Earth and out into space drops with the capture of Earth material into *gravitational* and *electrochemical dissipative structures*, the additional energy available for work results in more exergy captured in the building of more *dissipative structures*. The exergy captured as useful work in upstream *dissipative structures* is utilized as available work energy to build the heat engines of new downstream *dissipative structures*. The buildup of lengthening networks of *self-restoring* heat engines as more Earth materials are captured into cycles results in an increase in the net negative change in specific entropy of Earth as it transitions further away from thermodynamic equilibrium. This forms the basis of sustainable growth of an ecosphere on Earth.

The process of solar insolation power pouring down over a long period of time on all the material present in the gravity well of Earth results in five exergy-building phenomena that engage increasingly more material and energy in adding to available work energy, summarized in Table 2. We postulate the Earth ecosphere builds in a manner that maximizes three traits: *self-restoring order* characterized by *dissipative*

TABLE 2 Exergy building phenomena.

Exergy building phenomena
Phenomenon 1—Solar insolation and *gravitational dissipative structures* enable the formation of *electrochemical dissipative structures* by aggradation
Over the course of this time, more and more material captured in the gravity well of Earth is moved around by solar-power-driven gravitational heat engines, tidal forces, and seasons circulating air and water, wearing down material and the lithosphere, and transporting heavier elements by gravitational fluid flow to other locations where they can be made available for electrochemical reactions. Ongoing power input from solar insolation and the latent heat of formation of Earth provides heat for both endothermic and exothermic chemical reactions, resulting in *electrochemical dissipative structures* that are *semi-reversible* cycles of the build-up and break-down of chemicals. This increases the total mass captured into electrochemical heat engines in a process of building pairs of processes into cycles called "aggradation" (Patten, 1991).
Phenomenon 2—Heat engines with greatest efficiency have greatest fitness for survival
Thermodynamic efficiency of any given heat engine becomes a factor of its fitness for survival (Nielsen et al., 2020), either individually or through cooperative network relationships with other heat engines. Those heat engines with the greatest individual or cooperative thermodynamic efficiency generate the least amount of specific entropy and the greatest amount of specific exergy. This results in greater production per unit of time and out-competing other heat engines that utilize the same resources less efficiently.
Phenomenon 3—Instabilities and disturbances result in greater diversity and molecular complexity of heat engines
Natural instabilities occur when heat engines monopolize and create imbalances in the forms of resource depletion and byproduct excess (Prigogine and Wiame, 1946; Nicolis and Prigogine, 1971). The formation of such instabilities is the mechanism by which evolution takes place. Other forms of disturbances of a disruptive nature, such as meteor strikes, volcanic eruptions, and extreme weather patterns also contribute, resulting in the partial tear down of existing heat engine cycles and the formation of new heat engine cycles. A greater *functional diversity* of electrochemical heat engines is thus created with greater molecular complexities and greater efficiencies over time (Kay and Schneider, 1994; Nielsen et al., 2020).
Phenomenon 4—Heat engines link together in networks with greater total system throughput
New types of heat engines resulting from disturbances build off of the products and byproducts of existing heat engines, creating a series of interactions that link electrochemical heat engine cycles together in networks, resulting in the growth in area and *functional diversity* of the overall network (Ulanowicz, 1986; Christensen, 1992; Salomonsen, 1992; Nielsen and Ulanowicz, 2000; Jørgensen, 2007; Jørgensen and Ulanowicz, 2009; Jørgensen and Nielsen, 2014; Nielsen, 2019). *Network vitality* improves with robustness and reliability as competition results in a plurality of the total system throughflow of energy passing through fewer network connections while the majority of total system throughflow is maintained by a functionally diverse reserve of lower throughflow connections (Ulanowicz et al., 2008; Ulanowicz et al., 2014; Ulanowicz, 2018).
Phenomenon 5—DNA and life forms of greater complexity are formed by the phenomenon of hierarchic construction
Some of these electrochemical heat engine cycles network together in just the right way to form the first DNA structures and life under the radiation protection of Earth's magnetosphere. With life now formed, disturbances enable the adaptation, evolution, and hierarchic construction of life in greater varieties, with a diversity of life forms building off of other life forms in networks of production and consumption (Odum, 1969; Odum, 1971; Layzer, 1988; Jørgensen et al., 2000).

structures conditions present in the prebiotic Earth, *capacity* characterized by solar *power conditions* pouring down on the surface *area conditions* of Earth, and *organization* characterized by *network vitality conditions* and *functional diversity conditions* of the resulting biotic ecosystem. These phenomena and the empirical data collected for real ecosystems have been proposed to be observational evidence for a central hypothesis of ecological thermodynamics theory. This hypothesis was first formulated at a workshop in Møn, Denmark, August 1993, by J. J. Kay, S. E. Jørgensen, H. F. Mejer, S. N. Nielsen, and E. D. Schneider as a proposal for a fourth law of thermodynamics (Jørgensen, 2002, p. 164). Jørgensen et al. (2016, p. 58) states the latest form of the hypothesis:

> "A system that receives a throughflow of work energy will try to utilize the work energy flow to move away from thermodynamic equilibrium (more biomass, more structure, and more information), and if more combinations of components and processes are offered to utilize the work energy flow, the system will select the organization that gives the system as much work energy content (storage) as possible."

Jørgensen et al. (2016, p. 54) identifies three biological growth forms of ecosystem development under the ecological thermodynamics hypothesis, summarized in Table 3: increasing the amount of available work energy as stored biomass Eq. 4, stored genetic information (Eqs. 5 through 7), and total system throughflow in the growth of the network as whole (Eq. 8). We describe these as three *basal growth forms* that enable the increase in *self-restoring order* and *capacity* of a *basal* ecosystem through the natural selection of the *organization* that moves the entire ecosystem further from thermodynamic equilibrium. *Basal* human populations in the form of hunter-gatherers are a result of and are sustained by this *basal* ecosystem. The *basal* ecosystem provides the minimum human life support.

Humans capitalize on these types of growth forms to access *basal* exergy sources within the ecosphere to *augment* human society above what is *basally* produced by the ecosphere under *basal dissipative structures conditions*, *power conditions*, *network vitality conditions*, *functional diversity conditions*, and *area conditions*. By so doing, humans have utilized what we describe as three *augmentational growth forms*, a known and observed human activity, that are corollary to the *basal growth forms* described by Jørgensen et al.[4] This corollary is provided in Table 3. Using the *basal* ecosystem, humans have built their *augmentational* ecosystem under *augmentational power conditions*, *network vitality conditions*, *functional diversity conditions*, and *area conditions*. The *self-restoring order*, *capacity*, and *organization* of the *basal* ecosystem provides a fundamental basis for sustaining the *capacity* and *organization* of the human *augmentational* ecosystem.

4 The terms *basal* and *augmentational growth forms* are first defined in the present paper and are used in preference to the words "natural" and "artificial" to avoid implying a human externalism, exceptionalism, or supernaturalism by the distinction. Other biotic species can and do have *augmentational growth forms* when they modify their ecosystem for functional use. However, the questions being addressed are related to *human sustainability* and, thus, are focused on human activity.

TABLE 3 ***Basal growth hypothesis*** **and** ***augmentational growth corollary*****.**

Growth forms	Basal growth hypothesis	Augmentational growth corollary
Growth of biomass	Growth of physical structure biomass occurs with life forms increasing in size and population numbers. More of the incoming energy of high-quality solar radiation (on the order of 80%) is captured in the form of chemical work energy contained in greater quantities of biomass of existing biotic forms and new biomass of new biotic forms. Existing biomass requires ongoing throughflow of work energy for maintenance. The amount of stored available chemical specific work energy in biomass (u^{xC}) is provided in Eq. 4. (Jørgensen et al., 2016, p. 68) $$u^{xC} = 18.7\,\mathrm{kJ/g} \quad (4)$$	Growth occurs in average human size and in population numbers due to the *augmentational* mass production of food. *Augmentational* mass migration also results in less inbreeding, increasing the diversity in the genome of the human species.
Growth of information	Growth of information occurs in the form of more forms of life with DNA, and more complex forms of life with increasing lengths of DNA structures (replacement of r-strategist and small organisms with k-strategists and larger organisms). Life forms duplicate and pass more genetic and epigenetic information to subsequent generations for the optimization of energy use and evolutionary ascendancy. The stored available informational specific work energy for biotic node a (u_a^{xI}), Eq. 5, is calculated in terms of the biotic node's β-value (β_a), Eq. 6, and the Boltzmann informational molecular work energy (U_a^{BI}), Eq. 7 (Boltzmann 1905). (Jørgensen et al., 2016, pp. 68–72) $$u_a^{xI} = \beta_a u^{xC} \quad (5)$$ $$\beta_a = 1 + U_a^{BI} \cdot \left(\frac{NC_a \cdot NM_a}{m_a \cdot u^{xC}}\right) \quad (6)$$ $$U_a^{BI} = k_B T_a \ln M_a \quad (7)$$ NC_a—number cells of the biota a NM_a—number of molecules per cell of the biota a m_a—average mass in grams of an individual of the biota a k_B—Boltzmann's constant 1.38×10^{-23} J/molecule · K T_a—temperature of the biota a body in units of kelvin M_a—number of microstates of the biota a equal to 20^{NA_u}, with NA_u equal to the number of coded amino acids of the biota	Growth occurs of manufacturing process knowledge and automation technology that perform production algorithms. Growth occurs of knowledge and information, as well as technology for the storage, processing, networking, and movement of information as data.
Growth of network	Growth of network occurs using aggradation, resulting in more cycling of work energy through longer network paths with more branches and more indirect interconnections. "Total system throughflow" (*TST*), Eq. 8, increases, calculated in terms of "throughflow available work energy" from node *i* to node *j* (T_{ij}).[a] *TST* is the sum of all available work energy that passes into the network from the heat source (*0*),[b] out of the network to the heat sink (*N+1*), and between (from *i* to *j*) all nodes (*N*) of the network. (Jørgensen, 2002, pp. 214–215; Jørgensen and Ulanowicz, 2009) $$TST = \sum_{i=0}^{N} \sum_{j=1}^{N+1} T_{ij} \quad (8)$$	Growth occurs of human supply chain networks that move natural and produced resources to where they are needed, communication networks, and information networks.

[a]The values of throughflow available work energies can be calculated in terms of power per unit area, mass per unit area per unit time, or other form of exergy unit equivalence. When a throughflow is the consumption of the biomass of producer *i=a*, the throughflow (T_{ij}) is the product of the mass-rate of consumption and the specific exergy of the producer *i* = *a* ($u^{xC} + u_a^{xI}$).
[b]None of the *growth forms* include a discussion of the abiotic geophysical and biogeochemical *dissipative structures* that are the foundation of the ecosphere. However, calculations of total system throughflow, Eq. 8, include the throughflow available work energy coming from the abiotic *dissipative structures* of the ecosphere as initial inputs to the network (i.e., each *i = 0* for all *j = 1* through N).

1.2 Consequences for human migration into space

If the current state of human civilization on Earth were to be placed in an ecosphere with lesser *basal self-restoring order*, *capacity*, and *organization* than present on Earth, then humans would have access to less exergy in an ecosphere that is closer than Earth to thermodynamic equilibrium. It would be like expecting your car to run with a cell phone battery. The consequences that can be drawn from the preceding discussion are that human civilization would decline to a level of *basal* ecosphere *self-restoring order*, *capacity*, and *organization* that is sustainable by the available exergy. The implication in terms of the three *augmentational growth forms* in Table 3 is that decay of exergy in the human *augmentational* ecosystem would result. Over time and in an uncontrollable and unpreventable way, supply chains would disappear, market resources would be depleted, advancement in human pursuits would be disrupted, social and governance systems would falter or collapse, human population numbers would decline, genetic diversity in the human genome would be lost, average human individual biomass would decrease, and human knowledge and understanding would be forgotten.

The answer to sustaining the human enterprise as it tries to expand into space has at its heart an understanding that such expansion cannot be in such a way that humans decline in the long term. In the short term, such a reversal of growth would appear as failed settlements. A failed settlement could be an outpost where the humans have lost Earth support, forced to survive on an insufficient production of *basal* ecosystem exergy. Over time, such an isolated settlement of humans could deteriorate in ways discussed in the previous paragraph. The answer of how to sustain humans in space requires an understanding of the *basal* ecosystem of Earth and an ability to duplicate the conditions of that *basal* ecosystem in space. This should be the objective of environmental control and life support (ECLS) systems used in space.

The approach to date that has been used for providing ECLS for humans in space has been completely *augmentational*. The volume of spacecraft containing humans is minimized to reduce the size of the space that must be controlled. Technology generates the resources that humans need. Such technology is also necessarily limited in size and uses irreversible forced heat engines designed by humans that have high power densities resulting from the concentrated consumption of energy and a concentration of non-conservative forces that are added to drive cycles (e.g., real pumps). Compared to the *basal self-restoring* heat engines on Earth that provide the *basal* human life support, the use of technology for life support results in a greater entropy generated per unit of energy consumed to drive the cycles. It also results in the need for maintenance against wear, as well as the eventual failure of the technology due to entropy. *Augmentational* human technology is ultimately non-self-restoring. Such *augmentational* means of life support are inherently unsustainable by themselves. A *basal* ecosystem must be actively producing exergy that an *augmentational* ecosystem needs to operate. An *augmentational* ecosystem in space requires the exergy production of Earth—or someplace like Earth.

To better comprehend the difference between *augmentational* systems and *basal* systems beyond the theoretical discussion of conservative *versus* non-conservative forces, entropy, and exergy, consider everything on Earth that does not require human work or input. As an example, breathing is a passive activity for humans. The production of oxygen by the Earth ecosphere is performed without active human involvement. *Basal* life support on Earth requires no effort by humans for it to be available to humans. Now consider the amount of human effort required to make a technological (i.e., *augmentational*) system operable and indefinitely available off planet Earth, where humans would not have a *basal* ecosphere from which to passively draw oxygen. Generating air to breath becomes an active working effort to operate and maintain the *augmentational* systems required to create the oxygen and scrub the air of the exhaled carbon dioxide. The maintenance of such systems includes a support infrastructure of industry and knowledgeable humans on Earth to continue to provide repair parts and handle issues of malfunction, part and technology obsolescence, and supplier market changes as they occur. The operation also requires power technology and possibly fuel, both of which come with their own support infrastructures. All the oxygen generation technology, power technology, human societal effort, and industry that would be needed to just breath in space would be new in our lives as such. How much extra, non-passive support would be required?

And that is only the oxygen.

The nature of non-self-restoring *augmentational* systems that utilize irreversible cycles is that they require *self-restoring basal* systems that utilize *semi-reversible cycles* to be sustained. This is known as strong sustainability (Pelenc et al., 2015; Maiwald, 2023). The International Space Station would not be able to function without ground support from Earth and the *basal* ecosystems of Earth to support all of it. Moving further out into space, ground support from Earth becomes more difficult, more costly, riskier. This suggests that the weak sustainability of technofixes (Huesemann and Huesemann, 2011) as has been the to-date approach for deep-space missions is risky for human life. However, solutions that maximize *self-restoring* elements in a *basal* ecosystem approach, even if they do not have all that are present on Earth, might reduce the risk of failure.

These considerations suggest what Pirni (2016) calls an "anthropology of limit" to the human endeavor of migration into and habitation of space. Holy-Luczaj and Blok (2019) recognize the need of human life to be conative to the natural environment and the natural environment to be responsive to human life to sustain the integrity of human function on Earth. They raise the question of whether technology, biomimetic technology, or hybrids can be used to improve such conativity and responsiveness. Nielsen (2006) posits that eco-mimetic technology rather than biomimetic technology is needed to achieve sustainable production in human society, but that more studies are needed to understand how to use the *basal* properties of ecosystems in societal systems. The attempt to move life into space, effectively presenting life with a more extreme environment than on Earth, extends these ontic and ontological questions to space. The evidence suggests that the ability of humans and Earth-life to adapt to space is problematic, with the use of technology to simulate *basal* Earth life support also having challenges. The trade-off of trying to establish a *basal* life support system in space is that it would effectively need to be like Earth. The question is whether that is possible? Before we consider the possibility, we need to understand what it means to have a location in space outside of Earth be "like Earth." The ideas presented in this paper extend the science of ecological thermodynamics theory into space.

1.3 Thesis

The results of research into the beforementioned questions are presented in Section 2 as a *pancosmorio theory of human sustainability*. The theory is developed based on the science of ecological thermodynamics theory using the methodology of abductive reasoning (Pfister, 2022). A description of the theory (Section 2.1) is provided that has as its *factual consequent*: i) *there are conditions from which human life has evolved*, ii) *such conditions are required to sustain human life at its current level of growth*, and iii) *the availability of such conditions to humans defines the limit of their world*. This is followed by two *propositional antecedents* and nine *conditionals* that can be abductively reasoned from this *factual consequent* in support of the *propositional antecedents*. Four analytical models of *levels of sustainability* in space (Section 2.2) and five testable *pancosmorio hypotheses* (Section 2.3) are provided. Section 3 contains a discussion of the elements of the theory, referring to the supporting body of research in the physical, ecological, and social sciences. It also contains a new *quantitative method of human sustainability* that is used in the theory. The methodology builds on and formalizes the proposals in the perspective presented by Irons and Irons (2021), presenting a method for quantifying the *human sustainability* of any context in which humans are a part, including on Earth or in space. Conclusions are drawn in Section 4 on the application to sustainable development and the potential for the use of a balanced sustainability approach to solve the challenges presented by the theory. Conclusions are also drawn regarding implications for the Fermi paradox.

2 Theory

2.1 Pancosmorio theory of human sustainability in space

The *pancosmorio*[5] *theory of human sustainability*, hereinafter referred to as the *pancosmorio theory*, has one *factual consequent* that comes from ecological thermodynamics theory. It is supported by two *propositional antecedents* and nine *conditionals*, described in Sections 2.1.2 and 2.1.3. Discussion of the supporting science for each element of the theory is presented in Section 3.1 through Section 3.4.

2.1.1 Earth ecosphere factual consequent

There are conditions from which human life has evolved. Such conditions are required to sustain human life at its current level of growth. The availability of such conditions to humans defines the limit of their world.

The following *propositional antecedents* are new to ecological thermodynamics theory in that they expand the science from Earth into the realm of space.

2.1.2 Equivalent basal growth propositional antecedent

The first *propositional antecedent* is new to ecological thermodynamics theory, is based on the *basal growth hypothesis*, and infers the *factual consequent*: *basal* life activity can be sustained in any space location that has *self-restoring order*, *capacity*, and *organization* equivalent to the *basal* ecosphere in which such life evolved on its home planet. For humans, the base or settlement in space would need to be supported by ecosystems like what humans evolved with on Earth.

The following *conditionals* are written in the context of human life to connect the general form of the propositional antecedent to the specific factual consequent of human life on Earth.

2.1.2.1 Basal dissipative structures conditional

The first *conditional* is new to ecological thermodynamics theory, is based on the *basal growth hypothesis,* and implies the first *propositional antecedent*: *basal self-restoring order* in space requires *dissipative structures conditions* equivalent to those provided by Earth, *Gravitational dissipative structures* include geophysical and biogeochemical cycles driven by gravity and gradient air pressure, heating of the lithosphere provided by latent heat of formation, seasons and tidal forces driven by the Sun-Moon-Earth gravi-dynamic system, radiation protection provided by the electromagnetic dynamo of Earth. These *gravitational dissipative structures* are also necessary for the continuous function of the *electrochemical dissipative structures* of the biochemical and biophysiological cycles that make up Earth life.

2.1.2.2 Basal power conditional

The second *conditional* is new to ecological thermodynamics theory, is based on the *basal growth hypothesis,* and implies the first *propositional antecedent*: *basal capacity* in space requires *basal power conditions* available to match the power in quality and quantity that is bas*ally* available to the ecosphere of Earth. This equivalence is necessary to power the growth in total system throughflow exergy. The major contributors to this power are solar insolation at 239 W/m^2 and gravity at 95 W/m^2, for a total minimum requirement of 334 $W/m^{2.}$ of the area comprising both the *basal* and *augmentational* areas of the base or settlement. Production of power by the other *gravitational dissipative structures* (e.g., the radiation and solar wind shielding provided by the electromagnetic field of Earth) are factors, though the power levels are relatively minimal relative to solar insolation and gravity. Such contributors of power must be considered in the functional services they provide on Earth that are required at the location in space (e.g., the function of providing shielding against radiation).

2.1.2.3 Basal network vitality conditional

The third *conditional* is existing science in ecological thermodynamics theory, is based on the *basal growth hypothesis,* and implies the first *propositional antecedent*: *basal organization* in space requires *basal network vitality conditions* of a network that is robust to enable system *persistence* under nominal *loads.* Network robustness is characterized by a *window of vitality* that frames network *effective connectivity* between the values of one and three and *effective number of roles* between 2 and 4.5. The network is to provide equivalent production to a *basal* network on Earth.

2.1.2.4 Basal functional diversity conditional

The fourth *conditional* is existing science in ecological thermodynamics theory, is based on the *basal growth hypothesis,* and implies the first *propositional antecedent*: *basal organization* in space requires *basal functional diversity conditions* of abiotic and biotic resources that are sufficiently reliable to enable *basal* ecosystem *resilience* under *disruptions*. *Functional diversity* is characterized by a normalized *ascendency* between 36% and 44% and a normalized *reserve* of 56%–64%. *Functional diversity* is to provide ecosystem functions and services equivalent to the *basal* ecosphere on Earth.

2.1.2.5 Basal area conditional

The fifth *conditional* is new to ecological thermodynamics theory, is based on the *basal growth hypothesis,* and implies the first *propositional antecedent*: *basal capacity* and *basal organization* in space require *basal area conditions* of a geographic area sufficiently large to capture and route necessary levels of total

5 *Pancosmorio* is a protologism combining the Greek root words “pan” (neuter form of “pas”) meaning “all”, “kosmos” meaning “world”, and “orio” meaning “limit”.

system throughflow exergy to support network growth to enable *basal network vitality conditional* and the *basal functional diversity conditional* for *basal* ecosystem *persistence* and *resilience*. Based upon the size and population of Earth, the lower limit value is 60,500 m^2 *per capita* of the human population on location in space.

2.1.3 Equivalent augmentational growth propositional antecedent

The second *propositional antecedent* is new to ecological thermodynamics theory, is based on the *augmentational growth corollary*, and infers the *factual consequent*: *augmentational* life activity can be sustained in any space location that has *basal self-restoring order*, *capacity*, and *organization* equivalent to the home planet, as well as *augmentational capacity* and *organization* equivalent to civilization of that life on its home planet. For humans, the base or settlement in space would need to be supported by a *basal* ecosystem and the same human infrastructure, technology, and society as on Earth, human systems that would need to be sustained by exergy throughflow of *in-situ* resources from the *basal* ecosystem, *augmentational* power systems, and *in-situ* agricultural production and manufacturing capabilities for all utilized food and technology.

2.1.3.1 Augmentational power conditional

The sixth *conditional* is new to ecological thermodynamics theory, is based on the *augmentational growth corollary*, and implies this second *propositional antecedent*: *augmentational capacity* in space requires additional *augmentational power conditions* equivalent to the level of *augmentational* power consumption utilized by humans on Earth at their current level of growth. This is necessary to power human society and the systems and technology that society runs on. The power requirement is estimated at 1900 W *per capita* of the human population on location in space.

2.1.3.2 Augmentational network vitality conditional

The seventh *conditional* is new to ecological thermodynamics theory, is based on the *augmentational growth corollary*, and implies the second *propositional antecedent*: *augmentational organization* in space requires *augmentational network vitality conditions* (i.e., infrastructure, technology, and society that produce all of the human products, services, knowledge, and information) sufficiently robust to enable system *persistence* under nominal *augmentational loads*. The *augmentational* network is aggradated with the *basal* network in a way that does not contribute to the *effective connectivity* and the *effective number of roles* and quantities of throughflow that do not push the combined network outside the *window of vitality*. The *augmentational* network is to provide equivalent production to an *augmentational* ecosystem on Earth.

2.1.3.3 Augmentational functional diversity conditional

The eighth *conditional* is new to ecological thermodynamics theory, is based on the *augmentational growth corollary*, and implies this second *propositional antecedent*: *augmentational organization* in space requires *augmentational functional diversity conditions* of abiotic and biotic resources that are sufficiently reliable to enable *augmentational* ecosystem *resilience* under *disruptions*. The *augmentational functional diversity* when combined with the *basal functional diversity* does not push the combined *functional diversity* outside of and, ideally, keeps it within the standard deviation of normalized *ascendency* between 36% and 44% and a normalized *reserve* of 56%–64%. The *functional diversity* is to contain ecosystem functions equivalent to the contemporary *augmentational* ecosystem on Earth.

2.1.3.4 Augmentational area conditional

The ninth *conditional* is new to ecological thermodynamics theory, is based on the *augmentational growth corollary*, and implies the second *propositional antecedent*: *basal capacity* and *basal organization* in space requires *augmentational area conditions* of a geographic area sufficiently large to support network growth to enable the *augmentational network vitality* and *functional diversity conditionals* for *augmentational* ecosystem *persistence* and *resilience*. The lower limit value for a human society based upon the United States of America is 4,600 m^2 *per capita* of the human population on location in space and includes land area for *augmentational* habitation and production zones (i.e., for agriculture and industry).

2.2 Analytical models

The *conditionals* of the theory are interpreted as *conditions* that an ecosphere separate from Earth must have for a human base or settlement to be sustainable. Any such ecosphere that has these *conditions* to a limited extent will have limited *human sustainability*. There are four *levels of sustainability* that are analytically modeled from the *pancosmorio theory*. Table 4 summarizes the application of the *conditionals* to the analytical models. Discussion of the supporting science for each model is presented in Section 3.5 and in Supplementary Presentation 3: *Pancosmorio Theory Sustainability Analytical Models*.

TABLE 4 ***Levels of sustainability*** **and criteria.**

Level of sustainability	*Self-restoring order*	*Capacity*	*Organization*
Level 1	✓	✓	✓
Level 2	✓	✓	*Network vitality* and/or *functional diversity conditionals* not met
Level 3	✓	*Power* and/or *area conditionals* not met	
Level 4	*Dissipative structures conditional* not met		

TABLE 5 Tests of hypotheses of the *pancosmorio theory*.

The growth hypothesis
Test: Perform a root cause analysis of an unplanned event that results in a temporary drop in production of an ecosphere that meets *level 1 sustainability* criteria to determine the causal load or disruption. Time series measures of human consumption resources would provide calculated actual values of *terraform specific threshold load consistence/terraform specific threshold disruption resistance* (will be 1 or less to validate hypothesis) and *terraform specific threshold load persistence/terraform specific threshold disruption resilience* (will be equal to 1 to validate hypothesis)
The blight hypothesis
Test: Perform a root cause analysis of an unplanned event that results in blight (i.e., a drop in production without a recovery) of an ecosphere that meets *level 2 sustainability* criteria. Time series measures of resources or throughflows would provide calculated actual values of *terraform specific threshold load consistence* (will be less than 1 to validate hypothesis) and *terraform specific threshold load persistence* (will be less than 1 to validate hypothesis)
The diversity loss hypothesis
Test: Perform a root cause analysis of an unplanned event that results in a diversity loss (e.g., a loss of a limited number of nodes of the network without a recovery) of an ecosphere that meets *level 2 sustainability* criteria. Time series measures of resources or throughflows would provide calculated actual values of *terraform specific threshold disruption resistance* (will be less than 1 to validate hypothesis) and *terraform specific threshold disruption resilience* (will be less than 1 to validate hypothesis)
The cascade failure hypothesis
Test: Perform a root cause analysis of an unplanned event that results in an actual cascade failure (e.g., a collapse of the ecosphere with major and multiple losses of production and network nodes) of an ecosphere that meets *level 3 sustainability* criteria. Use time series measures of resources or throughflows recorded over the course of the event to calculate actual values of *terraform specific threshold disruption resistance* (will be less than 1 to validate hypothesis) and *terraform specific threshold disruption resilience* (will be 0 to validate hypothesis)
The pancosmorio theorem hypothesis
Test: This hypothesis is validated by a failure of a base or settlement to provide sufficient power from the combination of solar panels and power from non-solar-power sources as dictated by the theorem based upon the base's or settlement's distance from the Sun, which can then result in blight, diversity loss, or cascade failure. A base or settlement that meets the *dissipative structures* and *area conditionals* according to the theorem but still has sustainability problems is evidence that it can't achieve and maintain adequate *organization* due to inadequate *capacity* resulting from the *power conditional* not being met, either being too far from the Sun or having insufficient solar power collection sources for its non-solar power sources to be sufficient

2.2.1 Level 1 sustainability analytical model

Level 1 sustainability is met by the *basal dissipative structures conditional* providing *self-restoring order*, the *basal* and *augmentational power conditionals* and *area conditionals* providing ecosystem *capacity*, and the *basal* and *augmentational network vitality conditionals* and *functional diversity conditionals* providing ecosystem *organization* (i.e., within the *window of vitality* with *ascendency* and *reserve* in proper ratios to *capacity*). This is the level of an advanced human society in space that has solved its *human sustainability* problems. This is the minimum recommended level for human space bases and settlements that do not maintain a supply chain back to Earth.

2.2.2 Level 2 sustainability analytical model

Level 2 sustainability is met when *self-restoring order* and *capacity* are sufficient with *dissipative structures*, *power*, and *area conditionals* being met, but with insufficient *organization* resulting in a brittle network that is subject to blight and diversity loss under disturbances. Either the *basal* ecosystem is not sufficiently organized or the *augmentational* ecosystem excessively loads an organized *basal* ecosystem, resulting in the combined *network vitality conditions* and *functional diversity conditions* not meeting sustainable *organization* criteria. This is the level that provides humans with a familiar *basal* and *augmentational* environmental context that enables innovation and adaptation, with a minimal supply chain to replace depleted resources and specialized technology.

2.2.3 Level 3 sustainability analytical model

Level 3 sustainability is met when *self-restoring order* is established, but *capacity* does not sufficiently meet the *power* and *area conditionals* to sustain enough of a *basal network vitality* and *functional diversity* needed to ensure human adaptability. This results in sufficient *capacity* to build up enough *basal network vitality* and *functional diversity* for human life support, though there is insufficient *organization* of the combined *basal* and *augmentational* ecosystem to mitigate cascade failure following disturbances. This is only recommended as an early stage for a human space base or settlement that is supported by an supplemental supply chain[6] while working on transitioning to a higher *level of sustainability*.

2.2.4 Level 4 sustainability analytical model

Level 4 sustainability is the default when none of the *conditionals* are met. This results in insufficient *self-restoring order*, *capacity*, and *organization* to be able to support human life without Earth support. The *augmentational* system provides for ECLS system function and a supporting supply chain from Earth. This is only recommended for locations within Earth orbit that maintain an umbilical supply chain.[7] This level is recommended only for staffed missions in near-Earth orbit and unstaffed missions of any lengthy duration beyond Earth orbit.

2.3 Hypotheses

Out of this theory, we provide five testable hypotheses. These hypotheses will be testable by the results of human missions,

6 Supplemental supply chain support can be defined as a supply chain that provides all *augmentational* resources for the *augmentational* ecosystem to provide human life support and to support the building of the *basal* ecosystem.

7 Umbilical supply chain support is defined as a supply chain that incorporates a space location into the Earth *basal* ecosystem and provides all of the *augmentational* resources for human life support.

TABLE 6 Variables of the *pancosmorio theorem hypothesis*.

Variables of the *pancosmorio theorem hypothesis*	
N_{AU} (solar distance ratio)	The maximum number of astronomical units the settlement can be from the Sun and still achieve *level 1 sustainability*
C_{SI} (coefficient of solar insolation)	The ratio of the average incident solar insolation power per unit area entering Earth atmosphere (341 W/m2) to the natural power available per unit area to Earth ecosphere (334 W/m2); this is equal to 1.02 based upon the *power conditional* of the *equivalent basal growth propositional antecedent*
N_{SPA} (solar power panel area ratio)	The ratio of solar power panel area to land area under human use
e_{sp} (solar power panel efficiency)	The efficiency of the solar power panel technology being used; current maximum efficiency of solar power technology in space is approximately 0.342 (France et al., 2022); this paper considers current best-case conditions of 0.33 efficiency
N_{NSP} (non-solar power availability ratio)	The ratio of non-solar power availability per unit area of terraformed area to the natural power available to Earth ecosphere per unit area (334 W/m^2, based upon the *power conditional* of the *equivalent basal growth propositional antecedent*)

bases, and settlements as they migrate out into the Solar System and experience unplanned events of loss of productivity, blight, diversity loss, and cascade failure. Alternatively, failure mode tests can be designed and terraformed test platforms built in extreme environments on Earth or in space to test these hypotheses without putting life at risk. The tests for falsifiability of these hypotheses are summarized in Table 5. The tests use the *quantitative method of human sustainability*. Discussion of the supporting science for each hypothesis and this method are presented in Section 3.6.

2.3.1 The growth hypothesis

Any human base or settlement in space operating at *level 1 sustainability* can experience *basal* and *augmentational* growth that sustains all planned *loads* robustly without resulting in *load*-driven *disruptions* and with a minimum of time to reliably adapt in efficiency to unplanned *loads* and *disruptions*. This would appear as no drops in productivity under planned *loads* and temporary drops in productivity as *basal* and *augmentational* networks adapt in response to an unplanned *load* or *disruption*, taking time to recover. The result can be an improved ecosphere with improved *human sustainability*.

2.3.2 The blight hypothesis

Any human base or settlement in space operating at *level 2 sustainability* or lower can experience *basal* and *augmentational* networks faltering under planned *loads* but without any subsequent *disruption*. This lack of robustness would appear as ecosystem blight and a limited loss of *basal* and *augmentational* production. The result can be a loss of ability to sustain planned *loads*, requiring corrective and preventative changes to restore production.

2.3.3 The diversity loss hypothesis

Any human base or settlement in space operating at *level 2 sustainability* or lower can experience *disruptions* driven by planned *loads* and lack of full recovery from any *disruption*. This lack of reliability would appear as a limited loss of *functional diversity* from *basal* and *augmentational* ecosystems. The result can be local extinctions of species and loss of technological capability.

2.3.4 The cascade failure hypothesis

Any human base or settlement in space operating at *level 3 sustainability* or lower can experience *disruptions* without recovery. This would appear as a cascading loss of both production and *functional diversity* of both *basal* and *augmentational* ecosystems. A cascading loss would appear as a resource becoming fully depleted with no further production of that resource occurring, and a chain reaction risking total loss of other resources. The result would be a need to establish emergency supply chain support from another location or abandon the location to save life.

2.3.5 The pancosmorio theorem hypothesis

There is a maximum number of astronomical units from the Sun out to which a terraformed system is *basally* sustainable (assuming *dissipative structures*, and *area conditionals* are met) based upon meeting the *basal power conditional* with solar power panel area in use and the availability of non-solar power. Eq. 9 provides the mathematical form of the *pancosmorio theorem*. See Supplementary Presentation 2: *Pancosmorio Theorem Proof* for the development of the proof. The *pancosmorio theorem* is used to determine the combination of power from solar panels and power from non-solar-power sources that is needed to meet the *basal power conditional* to enable achieving and maintaining the *organization* necessary for *level 1 sustainability* at the distance it is planned to be from the Sun. See Table 6 for definitions of the variables.

$$N_{AU} \leq \left[C_{SI} \cdot \left(\left(e_{SP} \cdot N_{SPA}\right) + 1\right) / \left(1 - N_{NSP}\right)\right]^{\frac{1}{2}} \tag{9}$$

3 Discussion

3.1 Theoretical basis

The *conditions* required to sustain humans are empirically and factually associated with Earth where life evolved and can be determined in contrast to observable space where human life does not exist. Life on Earth is a factual consequence of the existence of these *conditions*. This is the fundamental basis of ecological thermodynamics theory. The *pancosmorio theory* expands upon the ecological thermodynamics theory by

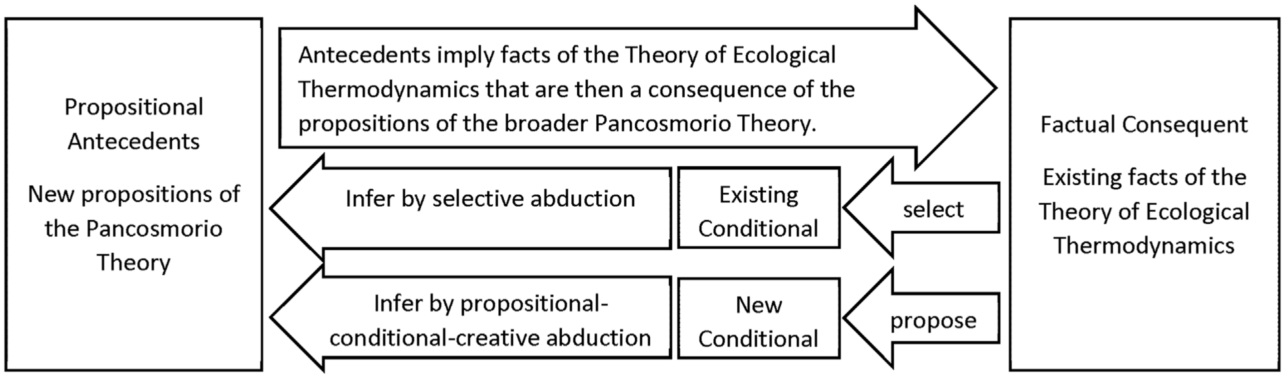

FIGURE 3
Abductive reasoning of the *pancosmorio theory*. The theory of abduction allows for the expanding of a fact (i.e., the factual consequent) to infer broader propositions (i.e., the propositional antecedents). The propositions, if proven true, establish a more encompassing theory (i.e., antecedence), of which the narrow, understood fact is one implied phenomenon (i.e., consequence). Science must then prove the broader propositional antecedents inductively by hypotheses and experiments to establish a more complete theory. The *pancosmorio theory* has one factual consequent as existing facts of ecological thermodynamics theory, two propositional antecedents that are new propositions to science as developed in the *pancosmorio theory*, two *conditionals* that are known existing conditions of ecological thermodynamics theory and infer one proposition of the *pancosmorio theory* by selective abduction, and seven *conditionals* that are newly proposed for ecological thermodynamics theory and infer the propositions of the *pancosmorio theory* by propositional-conditional-creative abduction. The propositional antecedents imply facts of ecological thermodynamics theory.

explaining what this means for human life and other Earth life to exist in any location in space.

The *pancosmorio theory* is developed using scientific philosophy and the theory of abduction (Pfister, 2022) (Figure 3). Abductive reasoning is necessary to infer a broader explanation of the existence of Earth and its ecosphere. When proven inductively by hypotheses and experiments, such a broader explanation can then be used deductively to apply to any location where humans attempt to establish an ecosphere outside of Earth. Risk to human life in the application of this theory is best mitigated by use of analog test platforms either on Earth or in space that do not involve human life or that have safety measures to protect humans. Such analogs could then be used as inductive experimental proofs of the *pancosmorio hypotheses*.

3.2 Dissipative structures and power conditionals

Research on Earth's energy budget (Kiehl and Trenberth, 1997; Loeb et al., 2009; Trenberth et al., 2009) has determined that the average amount of power going into Earth's atmosphere from solar insolation is 341 W/m^2. Of this amount, 102 W/m^2 is reflected from clouds, atmosphere, and snow and ice back into space. This means that 239 W/m^2 from solar insolation enters the ecosphere network and becomes exergy. Of the 239 W/m^2, 175 W/m^2 is converted into direct heating of the atmosphere, evaporation and entrainment of water in the atmosphere, convection, and turbulence. Except for the amount that is used for the latent heat of evaporation of water, 80 W/m^2, this power is used to overcome gravity, with gravitational potential energy stored in the gravitational field generating the power to return the air mass and water to its elevation of origin. Thus, the rate of gravitational energy input to the ecosphere through *self-restoring* gravitational heat engines is (175–80) W/m^2, or 95 W/m^2, equivalent to the amount of power from solar insolation that is required to lift the air and generate the gravitational potential energy. Thus, we arrive at an estimate of energy input rate per unit area of (239 + 95) W/m^2, or 334 W/m^2.

There are other functional systems of note that generate power and provide vital functions to Earth life. The rotation and the resulting diurnal warming and cooling of the Earth, water, and air result in weather patterns that generally move west to east. An annual revolution of Earth around the Sun, a tilt of the Earth axis relative to its plane of revolution, and the revolution of the Moon around Earth also result in seasons and tidal forces. The lithosphere is heated by latent heat of the original gravitational collapse of Earth as well as ongoing energy input to the lithosphere from the tidal forces. Earth is protected by a magnetosphere from the solar wind that would otherwise generate high energy radiation on Earth and strip away water and gases from the atmosphere and hydrosphere. The magnetosphere is generated by an electromagnetic dynamo of circulating and electrically charged molten liquid matter in the core of Earth also formed out of the original gravitational collapse. Earth rotates on an axis, resulting in a diurnal variation of solar insolation. All of these *dissipative structures* are a result of the gravitational formation of Earth in orbit of the Sun. They are necessary to sustain life and must be provided for life when outside of Earth.

Gravity is also needed to sustain the biochemical and biophysiological function of humans and other biotic lifeforms. The mostly anecdotal and observational results of life-science research in gravitational orbit around Earth (e.g., see example reviews provided by Kandarpa et al., 2019; Kordyum and Hasenstein, 2021; Bijlani et al., 2021) provide evidence that living things do not function in the same way or at the same level of performance and efficiency in an inertial free-fall reference frame where there is gravity without apparent weight and centripetal force without apparent centrifugal force. Even with a space capsule pressurized to the same level of atmospheric pressure that exists at altitudes where humans live on Earth, the lack of weight and centrifugal force means that there is no fluid pressure gradient within the biotic organism body (see Supplementary Presentation 1: *Pancosmorio Theory Classical Mechanics Clarifications* for discussion of Forces on the Human Body in the Free-Fall of Space), which is a likely factor in the dysfunction of the human body and other organisms in space.

Our era of the Anthropocene is characterized by a contribution of humans to the total system throughflow of the Earth ecosphere in the burning of fossil fuels that are the stored exergy of past solar insolation being rerouted through the ecosphere. Based on the research of Syvitski et al. (2020), this *augmentational power conditional* is estimated to be 1900 W *per capita* of the human population on Earth. This is power that is in addition to the *basal power conditional*. Compared to the *basal power* required just to establish and maintain the natural part of the ecosphere, this might seem like a minor amount. However, it adds up quickly as the local population rises.

3.3 Network vitality and functional diversity conditionals

The objective of *organization* is a network that matches that of an equivalent Earth ecosystem in persistence and resilience to achieve *human sustainability*. As noted in Section 3.2, one element of *persistence* and *resilience* is an ongoing supply of sufficient power. That power must then be utilized by the ecosphere. The intuitive thinking has been that maximized biodiversity and maximized thermodynamic efficiency are requirements for sustainable power utilization. Solid theoretical justification is ambiguous at best for a positive relationship between biodiversity and sustainability (McCann, 2000; Loreau et al., 2001; Loreau and de Mazancourt, 2013). Ulanowicz (1997, Ulanowicz, 2002, Ulanowicz et al., 2008, Ulanowicz, 2009, Ulanowicz et al., 2014, Ulanowicz, 2018, Ulanowicz, 2020) has established by theoretical development and correlative, empirical evidence of Earth ecosystem network data that there is a network variety (H) comprised of a network constraint (A) and a network flexibility (Φ). In total *capacity* ($H \cdot TST$; see Table 3 for definition of TST), the network provides *ascendency* ($A \cdot TST$) and *reserve* ($\Phi \cdot TST$). Functionally, *ascendency* is a measure of the throughflow that is passing through the most stable of the network links and *reserve* is a measure of the throughflow passing through all the other links with a greater diversity of links resulting in a greater *reserve*. The relationship between *ascendency* and *reserve* is characterized by Eqs 10 through 13.

$$H = -\sum_{i=0}^{N}\sum_{j=1}^{N+1}\left\{\left(\frac{T_{ij}}{TST}\right)\cdot \ln\left[\frac{T_{ij}}{TST}\right]\right\} \tag{10}$$

$$A = \sum_{i=0}^{N}\sum_{j=1}^{N+1}\left\{\left(\frac{T_{ij}}{TST}\right)\cdot \ln\left[\frac{T_{ij}\cdot TST}{\sum_{j=1}^{N+1}\left(T_{ij}\right)\cdot\sum_{i=0}^{N}\left(T_{ij}\right)}\right]\right\} \tag{11}$$

$$\Phi = -\sum_{i=0}^{N}\sum_{j=1}^{N+1}\left\{\left(\frac{T_{ij}}{TST}\right)\cdot \ln\left[\frac{\left(T_{ij}\right)^2}{\sum_{j=1}^{N+1}\left(T_{ij}\right)\cdot\sum_{i=0}^{N}\left(T_{ij}\right)}\right]\right\} \tag{12}$$

$$H = A + \Phi \tag{13}$$

Functional diversity of the ecosystem is characterized by a normalized *ascendency* (a; a measure of the degree of organization of the network) between the values of 36% and 46% and a normalized *reserve* (ϕ; a measure of the degree of freedom of the network) between the values of 56% and 64%. This normalized *reserve* enables *persistence* that presents as a network reliability against external disturbances (Ulanowicz, 2009; Ulanowicz, 2020). Normalized *ascendency* and normalized *reserve* are provided by Eqs 14, 15.

$$a = A/H \tag{14}$$

$$\phi = \Phi/H \tag{15}$$

The normalized *ascendency* enables *resilience* that presents as a network robustness and is further characterized by a *window of vitality* (Ulanowicz, 2009; Ulanowicz, 2020). The *window of vitality* frames network *effective connectivity* (c), a measure of the weighted average number of links through which the throughflow is passing, between the values of one and three and the network *effective number of roles* (r), a measure of the weighted average number of trophic levels through which the throughflow is passing, between the values of 2 and 4.5 (Ulanowicz et al., 2014; Ulanowicz, 2020). The relationship between them is characterized by Eqs 16, 17.

$$c = \prod_{i=0}^{N}\prod_{j=1}^{N+1}\left(\frac{\sqrt{\sum_{j=1}^{N+1}\left(T_{ij}\right)\cdot\sum_{i=0}^{N}\left(T_{ij}\right)}}{T_{ij}}\right)^{T_{ij}/TST} \tag{16}$$

$$r = \prod_{i=0}^{N}\prod_{j=1}^{N+1}\left(\frac{T_{ij}}{\sum_{j=1}^{N+1}\left(T_{ij}\right)\cdot\sum_{i=0}^{N}\left(T_{ij}\right)}\right)^{T_{ij}/TST} \tag{17}$$

The assumption is that there must be a diversity of abiotic and biotic resources equivalent to a matching Earth ecosystem. Modeling and comparison to real ecosystem networks provides key parameters to consider in building the network. The goal is to achieve a quantitative *capacity* ($H \cdot TST$) that is equal to that of the equivalent Earth ecosystem with a 40%–60% balance of *ascendency* to *reserve* and the network within the *window of vitality*. The *pancosmorio theory* asserts that the establishment of the *dissipative structures*, *power*, and *area conditionals* provided for the *basal* system (see Section 3.4) ensures that sufficient *self-restoring order* and *capacity* can support the network. How the network is built utilizing *functional diversity* will determine whether it is within the *window of vitality*.

How *network vitality* and *functional diversity* are used to build an ecosystem matter. Experiments performed to-date of human-designed ecosystems that are closed to a complete or partial (quasi-closed) extent from the ecosphere of Earth result in local ecosystem dysfunction, even on Earth. Biosphere 2 (Allen et al., 2003; Gitelson et al., 2003, page 52) was an example of attempting to contain a high diversity within a closed system without proper network *organization;* biomes requiring different environmental conditions were juxtaposed in close proximity due to insufficient area, likely resulting in disturbances of proper throughflows of the biomes' networks. Biosphere 2 also failed to consider the impact of *augmentational* human systems and technology and their integration into the *basal* network.

The establishment of a local ecosystem in space likely requires the formulation of an ecosphere network in a managed stepwise fashion. Irons (2018) suggests a boot-strapping effort to establish three zones (i.e., a habitation zone, an agricultural zone, and an

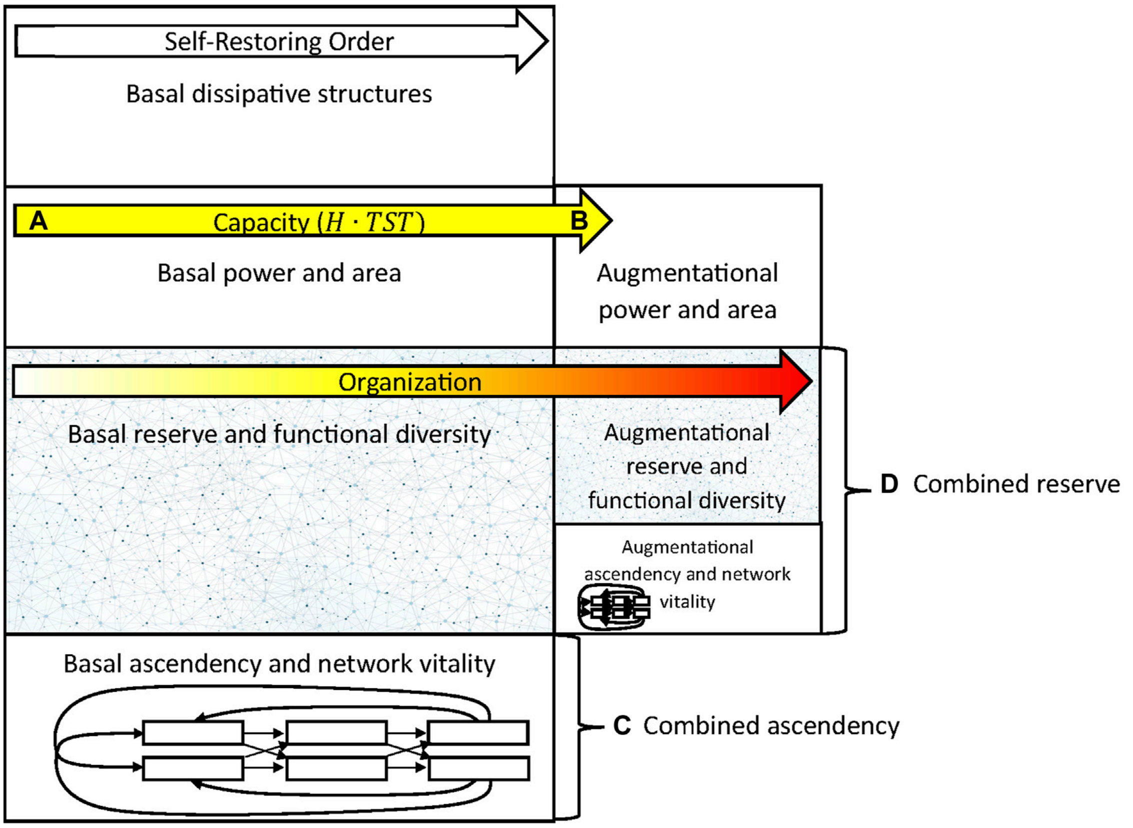

FIGURE 4
Visual of an ecosphere that meets all *conditionals*. The end objectives are: **(A)** *Basal* ecosystem carries most of the total system throughflow (*TST*). **(B)** *Augmentational capacity* is a small percentage of the total system throughflow (*TST*) coming from the *basal* ecosystem. **(C)** The *basal* ecosystem provides all of the combined *ascendency* at 36%–44% of combined *capacity*. The *ascendency* ensures the combined network has an *effective connectivity* and an *effective number of roles* within the *window of vitality*. Shown is an example effective network with two links per node and three roles. Each link in the *augmentational* network, including the links that most contribute to *augmentational ascendency,* must have an amount of throughflow that is relatively minor compared to the throughflow going through the links of the *basal* network that most contribute to the *effective connectivity* and the *effective number of roles*. **(D)** Combined *reserve* is made up of a less than 56%–64% of the *capacity* of the *basal* network combined with all of the *capacity* (i.e., *reserve* and *ascendency*) of the *augmentational* network, making up 56%–64% of the combined *capacity*, such that it does not pull the combined network outside of the *window of vitality*. The *augmentational ascendency* must mostly contribute to the combined *reserve*. Minimizing the impact of the *augmentational* network is also accomplished by aggradating (i.e., recycling) waste material of the *augmentational* network back into the *basal* network.

ecological buffer zone) using expedited primary succession, competitive redundancy, and ecological service reservoirs. This might be sufficient to get things started but would eventually have to proceed to a proportional fullness of network as exists in the Earth ecosphere. The key shown in Figure 4 is to aggradate the *augmentational* network with the *basal* network in a way that does not result in excessive contribution of the *augmentational* network to the *effective connectivity* and the *effective number of roles*. The *augmentational* network contribution to the combined network must also keep the combined normalized *reserve* between 56% and 64%.

The effort required to set up the full set of *basal* and *augmentational* ecosystems with optimum *network vitality* and *functional diversity* will involve a detailed level of environmental management to establish patches and populations of biotic species and communities of biotic interactions within local, regional, and biome-wide ecosystem architectures of abiotic accumulations and flows. This must be done in a way that leverages the established *dissipative structures*. Once all abiotic and biotic resources are established in appropriate locations and quantities, the sufficient levels of temperature, atmospheric pressure gradient, apparent weight, and physical and biogeochemical cycles provided under the *dissipative structures conditional* will tend to naturally drive interactions between producers and consumers as evidenced by their function in the Earth ecosphere. These interactions create nodes and links of the network. And as more interactions engage, the network expands across the landscape and builds. Competition with sufficient management should drive the ecosystem into the *window of vitality* with the proper balance of the *capacity* between the *ascendency* and the *reserve*.

3.4 Area conditionals

The *area conditionals* are at the crux of the relationship of all the *conditionals*. The *power* and *area conditionals* together determine the ecosphere *capacity*. The *power conditional* is in terms of power per unit area, therefore the total *area condition* of the ecosphere location in space will drive the total *power condition*. Diamond (1975) notes that when the area of an island or isolated ecosystem is not sufficiently large to support the diversity of biotic species, there will be local species extinctions that occur naturally. The body of work following Diamond's 1975 paper has confirmed this phenomenon (e.g., Connor and McCoy, 1979; Saunders et al., 1991; Caughley, 1994; Debinski and Holt, 2000; Margules and Pressey, 2000; Sayer et al., 2013). Thus, the *area conditional* also impacts *functional diversity* and the ecosphere *organization*.

The lower limit for the *basal area conditional* of 60,500 m^2 *per capita* ensures the current *basal* evolutionary and adaptive state of humans can be supported by the *capacity* and *organization* of the ecosphere. It is based upon the surface area (including water) of Earth of 196.9 million mi^2 divided by the current population of Earth of 7.837 billion equaling 65,100 m^2 *per capita*, followed by subtracting the *augmentational area conditional* of 4,600 m^2 *per capita*.

The lower limit for the *augmentational area conditional* of 4,600 m^2 *per capita* is based upon the population of the United States of 331.9 million and the combined urban and agricultural area of the United States of 63,400 mi^2 and 530,400 mi^2, respectively (National Land Cover Database, 2016). Agricultural land is included with urban land in the *augmentational area conditional* considering that human agriculture is *augmentational*. Human hunting and gathering for food are *basal* and supported by the *basal area conditionals*, allowing for human survivability when *augmentational* systems fail.

The combined area required to support one person is the size of a square 255 m on a side. The *per capita* land area might seem excessive. It is assumed that the level of human *augmentation* at any point in the history of Earth is efficiently adapted to the available *basal* and *augmentational* surface area on Earth based upon that time's human adaptation and technological advancement. Human civilization on Earth today utilizes the entire Earth to *basally* support human *augmentational* adaptation. A human settlement in space must be *basally* and *augmentationally* similar to a developed nation on Earth to be fully sustainable because that is what contemporary humans are adapted to.

3.5 Analytical models

The analytical models for *levels of sustainability* are based upon the way Earth evolved into an island of order. The steps that Earth proceeded through in its evolution of order are the building blocks of a functioning and sustainable ecosphere. *Self-restoring order* formed the early lithosphere, hydrosphere, and atmosphere using the *gravitational dissipative structures*. Power from the Sun poured down on the surface area of Earth to start the buildup of *capacity* with geophysical cycles and biogeochemical cycles. Ultimately life formed and, through patterns of growth of *electrochemical dissipative structures*, increased in *capacity* through the buildup of *organization* by way of *network vitality* and *functional diversity*. See Supplementary Presentation 3: *Pancosmorio Theory Sustainability Analytical Models* for further explanation of the *levels of sustainability*.

3.6 Hypotheses and terraform sustainability

The first four *pancosmorio hypotheses* utilize four parameters: *terraform threshold load consistence, terraform threshold disruption resistance, terraform threshold load persistence, and terraform threshold disruption resilience*. These are based on an approach to measuring human sustainability derived from stability properties of an ecosystem as first proposed by Irons and Irons (2021). Section 3.6.1 provides a refinement of the original framework into a *quantitative method of human sustainability*. The first four hypotheses are then explained in Section 3.6.2 in the context of the refined *quantitative method of human sustainability*.

Section 3.6.3 explains the *pancosmorio theorem hypothesis* as a limit to the *human sustainability* of a terraformed ecosphere. The implications are that humans will be limited in how far away from their home Sun they can terraform their environment to an ecosphere of *level 1 sustainability*. Any attempt to terraform a human base or settlement beyond the distance calculated by the *pancosmorio theorem* will likely undergo the problems predicted by the *cascade failure hypothesis* due to not meeting the *basal power conditional*.

3.6.1 Quantitative method of human sustainability

The *pancosmorio theory* uses a formalized *quantitative method of human sustainability* developed from the original terraform sustainability assessment framework proposed by Irons and Irons (2021). Human sustainability is defined by Irons and Irons for a bioregenerative life support system as a form of engineered ecosphere. *Human sustainability* as refined herein is for application to an entire human base or settlement in space. Table 7 compares the classification of disturbances in the original framework to the new method. The new method utilizes *threshold loads* and *threshold disruptions*, an approach to defining disturbances that enables the use of orthogonal measures of stability for quantifying *human sustainability*. See the Supplementary Presentation 4: *Pancosmorio Theory Orthogonal Stability Measures Analytical Model Discussion* for the development of the orthogonal stability measures of *threshold load stability* and *threshold disruption stability*. Using this refined classification system with the *pancosmorio theory* allows for testing of the hypotheses of Section 2.3.

Table 8 compares the original framework and the new method regarding the calculating of stability properties, explaining how the new disturbance classification system provides a means for calculating ecosphere stability. The *threshold load stability* of Figure P4.4 of Supplementary Presentation 4 is put in terms of *threshold load consistence* (C_m), Eq. 18 in Table 8, and *threshold load persistence* (P_m), Eq. 19 in Table 8. The *threshold disruption stability* of Figure P4.4 of Supplementary Presentation 4 is put in terms of *threshold disruption resistance* ($Rs_{a\neq m}$), Eq. 20 in Table 8, and *threshold disruption resilience* ($Rl_{a\neq m}$), Eq. 21 in Table 8. The method normalizes these measures of human sustainability using the same exact measures of stability in an equivalent Earth model. The results of the normalization are provided in Table 8 as four quantitative *terraform specific threshold stability properties*: *terraform specific threshold load consistence* (C_m^T), Eq. 22; and *terraform specific threshold load*

TABLE 7 Classification of disturbances. Comparison of terraform sustainability assessment framework (Irons and Irons, 2021) and *quantitative method of human sustainability*.

Classification of disturbances	
Terraform sustainability assessment framework	*Quantitative method of human sustainability*
Applied to bioregenerative life support systems (BLSS).	***Applied to the entire ecosphere of the human base or settlement in space.***
A *load* is any human activity that consumes provisioning services of an ecosystem. A *disturbance* is any event "that disrupts the structure of an ecosystem, community, or population, and changes resource availability or the physical environment" (White and Pickett, 1985).	***Loads* and *disruptions* are defined as subclassifications of disturbance to align with existing literature that describe disturbances that are like *loads* and *disruptions* but without having defined the terms *load* and *disruption*. A *load* can be any consumer of any resource in the ecosystem network, including but not limited to humans.** A *disturbance* is a phenomenon that acts to change an ecosystem. A *load* is a subclassification of disturbance that results in an increase in the consumption of resources at a rate that the network can accommodate without resulting in the complete loss of existing producers (i.e., the loss of a nodes of the network). A *disruption* is a subclassification of disturbance that results in one or more producer nodes being eliminated from an ecosystem network. Pulse and press effects are frequently studied in the context of major impacts to an ecosystem, such as fires, floods, heat waves, storms, species loss, biological invasions, and acidification, to name a few of the commonly studied disturbances (Jentsch and White, 2019). Depending on the various usages in the existing literature, pulse and press effects could be subclassified as either loads or disruptions on a case basis.
No proposal for identifying orthogonal stability properties.	**Orthogonal stability properties are defined.** *Threshold load stability* and *threshold disruption stability* (see the Supplementary Presentation 4: *Pancosmorio Theory Orthogonal Stability Measures Analytical Model Discussion*) are defined as measures of orthogonal dimensions of every producer of every resource in an ecosystem network. *Threshold load stability* is a measure of the stability of one producer and the amount of one resource it produces following a *threshold load* (when the one resource of the producer is subject to a *load*). *Threshold disruption stability* is a measure of the stability of the other producer nodes and the total amount of the resource they produce following a *threshold disruption* (when the one producer measured by the *threshold load stability* is eliminated from the network).

persistence (P_m^T), Eq. 23; *terraform specific threshold disruption resistance* ($Rs_{a\neq m}^T$), Eq. 24; and *terraform specific threshold disruption resilience* ($Rl_{a\neq m}^T$), Eq. 25. Table 9 then compares the approaches to determining *human sustainability* of the original framework and the new method.

3.6.2 Growth, blight, diversity loss, and cascade failure hypotheses

The *growth hypothesis* predicts a state of continued *human sustainability* of an ecosphere. The *basal* ecosystem is complete and the *augmentational* ecosystem is not excessive or wasteful but does support a complete human civilization and all of its technology. This results in *terraform specific threshold load persistence* and *terraform specific threshold disruption resilience* equal to one.

The *blight hypothesis* and the *diversity loss hypothesis* are both based on *level 2 sustainability*. For the former hypothesis, blight is a result of a lack of robustness when the network has excessive *effective connectivity* (i.e., too many links are carrying too much load) and/or excessive *effective number of roles* (i.e., too many *effective number of flows* in series pulling too much of a load). The result is a drop in *terraform specific threshold load consistence* and *terraform specific threshold load persistence* of throughflows in the network. For the latter hypothesis, diversity loss is a result of a lack of reliability when the network has insufficient normalized *reserve* (i.e., not enough *functional diversity*) to fill the gap in *ascendency* left by the diversity loss while also recovering in *reserve*. The result is a drop in *terraform specific threshold disruption resistance* and *terraform specific threshold disruption resilience* of throughflows in the network. This equates to the current sustainability struggle documented in human cities on Earth (e.g., Morello et al., 2000; Pope et al., 2009; Bergman et al., 2022; Zucaro et al., 2022). If we do things the same way in space as we have done on Earth, the struggle will be similar.

The *cascade failure hypothesis* is based on *level 3 sustainability*. This starts out like the *diversity loss hypothesis*, but results in a cascade of diversity losses due to weakness of the *network vitality* and *functional diversity*, resulting in *terraform specific threshold disruption resilience* dropping to zero. Just as there is evidence in existing populations of humans having successfully migrated all over Earth, there is evidence in the archeological and anthropological record of colony and society ecological collapse. It has even been the topic of popular science writing. Some claim it is human overconsumption of natural resources that drives collapse. Others critique this and say that collapse is frequently driven by other nations invading and enslaving a society and pillaging its lands to the point of its collapse. Still others point to natural cycles and catastrophes on Earth that can result in periodic *disruption* of human societies. Researchers who might disagree as to the cause of the ecological collapse of societies do agree on at least two points: 1) there is a record of societies collapsing and 2) each collapse correlates with *disruptions* (de Menocal et al., 2005; Diamond, 2005; Peiser, 2005; Hunt and Lipo, 2006; Diamond, 2011; Flexner, 2011; Butzer, 2012; Gause, 2014).

3.6.3 Pancosmorio theorem hypothesis

The development of Eq. 9 is provided in the Supplementary Presentation 2: *Pancosmorio Theorem Proof*. Eq. 9 is presented in a form that enables terraform engineers and designers to determine the quantities of solar power panels and non-renewable power generation needed to support the *basal* portion of the ecosphere

TABLE 8 Definition of ecosphere stability. Comparison of terraform sustainability assessment framework (Irons and Irons, 2021) and *quantitative method of human sustainability*.

Definition of ecosphere stability	
Terraform sustainability assessment framework	*Quantitative method of human sustainability*
Ecosystem control points (Bernhardt et al., 2017) are defined as "areas of the landscape that exert disproportionate influence on the biogeochemical behavior of the ecosystem under study." One identifies the ecosystem control points to select a subset of all interactions and factors. This requires a careful analysis to identify the measurable, disproportionately influencing factors of the biogeochemical cycles and environmental processes, supply chains, non-regenerative subsystems of the BLSS, and bioregenerative subsystems of the BLSS. These disproportionately influencing factors are called critical factors. The myriad possible ways that a system can be impacted by load feedbacks and disturbances necessitates limiting them to classes of load feedbacks and disturbances (Haimes, 2009). Stability properties have been proposed in early research to be resistance, resilience, persistence, and variability (Pimm, 1984). The stability of the BLSS as a result of a load is quantified using consistence (C), defined as "the ability to maintain functional output immediately upon establishment of a load" and Persistence (P), defined as "the ability to return to functional output while loading is ongoing". $C = Y2/Y1$ $P = Y3/Y1 - C$ The stability of the BLSS as a result of a disturbance is quantified using resistance (Rs), defined as "the ability to maintain functional output immediately following a disturbance" and Resilience (Rl), defined as "the ability to return to functional output after a disturbance has passed". $Rs = X2/X1$ $Rl = X3/X1 - Rs$ Symbols X and Y are used to differentiate disturbance critical factors (X) and load feedback critical factors (Y), though a given critical factor could be impacted by both disturbances and load feedbacks. Ecosystem control points for the given BLSS and its classes of disturbances and load feedbacks must be selected to meet five caveats identified by Nimmo et al. (2015) for use of these equations.	**The new orthogonal stability properties are calculated in terms of the throughflow available work energy of a critical factor resource at a control point in the ecosphere network.** The stability of the ecosphere as a result of a *threshold load* on a resource flowing from node m to node n is quantified using *threshold load consistence* (C_{mn}), Eq. 18, defined as "the stability of the production functional output of throughflow available work energy of the resource from producer node m to consumer node n as measured by the minimum at time 2 to which production falls following establishment of a *threshold load* at time 1" and *threshold load persistence* (P_{mn}), Eq. 19, defined as "the stability of the production functional output of throughflow available work energy of the resource from producer node m to consumer nodes n once the resource production by the producer node has leveled off at time 3 following the drop to a minimum at time 2 caused by a *threshold load* applied at time 1". The producer node being *threshold-loaded* is m and the consumer nodes that are consuming the resource produced by m are n, with n including the new consumer applying the new *threshold load*. $$C_m = \sum_n (T_{mn,2}/T_{mn,1}) \quad (18)$$ $$P_m = \sum_n (T_{mn,3}/T_{mn,1}) - C_m \quad (19)$$ The stability of the ecosphere as a result of a *threshold disruption* is quantified using *threshold disruption resistance* (Rs), Eq. 20, defined as "the stability of the production functional output of the remaining producer nodes of throughflow available work energy of the resource as measured by the minimum at time 2 to which production falls following a *threshold disruption* at time 1" and *threshold disruption resilience* (Rl), Eq. 21, defined as "the stability of the production functional output of throughflow available work energy of the resource from the remaining producer nodes of a resource once the resource production has leveled off at time 3 in recovery following the drop to a minimum at time 2 caused by a *threshold disruption* at time 1". The remaining producer nodes are $a \neq m$ and the consumers of the resource produced by nodes $a \neq m$ are nodes b. $$Rs_{a\neq m} = \left(\sum_{a\neq m,b} T_{ab,2}\right) \Big/ \left(\sum_{a\neq m,b} T_{ab,1}\right) \quad (20)$$ $$Rl_{a\neq m} = \left[\left(\sum_{a\neq m,b} T_{ab,3}\right) \Big/ \left(\sum_{a\neq m,b} T_{ab,1}\right)\right] - Rs_{a\neq m} \quad (21)$$ The theoretical objective is for the available throughflow work energies of critical factors at all control points in the ecosphere to remain stable over time (i.e., significantly constant or varying around a mean within an acceptable standard deviation).
The effect of environmental variance on the sustainability calculations of a BLSS are controlled by normalizing the stability properties to those of an equivalent (in bioregenerative aspects) Earth environment that would also be affected by variance. Terraform specific stabilities are the ratios of the value the stability properties of a BLSS (e.g., $\boldsymbol{Rs_{BLSS}}$) to the stability properties of the proportional Earth model (e.g., $\boldsymbol{Rs_E}$): terraform specific consistence ($\boldsymbol{C_T}$), terraform specific persistence ($\boldsymbol{P_T}$), terraform specific resistance ($\boldsymbol{Rs_T}$), and terraform specific resilience ($\boldsymbol{Rl_T}$). $C_T = C_{BLSS}/C_E$ $P_T = P_{BLSS}/P_E$ $Rs_T = Rs_{BLSS}/Rs_E$ $Rl_T = Rl_{BLSS}/Rl_E$	***Terraform specific stability properties* are applied to the entire ecosphere established at the human settlement or base in space.** They are the ratios of the value the stability properties of a human settlement or base in space (e.g., C^S_m) to the stability properties of the proportional Earth model (e.g., C^E_m): *terraform specific threshold load consistence* (C^T_m), Eq. 22; and *terraform specific threshold load persistence* (P^T_m), Eq. 23; *terraform specific threshold disruption resistance* ($Rs^T_{a\neq m}$), Eq. 24; *terraform specific threshold disruption resilience* ($Rl^T_{a\neq m}$), Eq. 25. $$C^T_m = C^S_m/C^E_m \quad (22)$$ $$P^T_m = P^S_m/P^E_m \quad (23)$$ $$Rs^T_{a\neq m} = Rs^S_{a\neq m}\big/Rs^E_{a\neq m} \quad (24)$$ $$Rl^T_{a\neq m} = Rl^S_{a\neq m}\big/Rl^E_{a\neq m} \quad (25)$$ The representative *terraform specific stabilities* of the ecosphere are the lowest values resulting from the selected scenarios of *loads* and *disruptions.*

based upon the distance from the Sun planned for the base or settlement. The examples of mixed-power settlements in Table 10 have a relative abundance of *in-situ* materials that can be used as sources of non-solar power (e.g., methane on Titan) to meet the *power conditional.* In each of these examples, the area of solar power panels used is equal to the total land area used for the human base or settlement. The efficiency of the solar power panel technology being used is 0.33, based upon current maximum efficiency of solar power technology being 0.342 (France et al., 2022). The results provide the level of non-solar power generation (i.e., $P_{NS} = N_{NSP} \times 334$ W/m^2) required for powering *basal growth* at *level 1 sustainability*. It is important to remember that, to achieve *level 1 sustainability*,

TABLE 9 Determination of *human sustainability*. Comparison of terraform sustainability assessment framework (Irons and Irons, 2021) and *quantitative method of human sustainability*.

Determination of *human sustainability*	
Terraform sustainability assessment framework	*Quantitative method of human sustainability*
When *X* and *Y* are selected to be the same human-consumer resources of a BLSS, the stability properties represent measures of human sustainability for the BLSS.	**When one of the consumers of nodes *n* and *b* in Eqs 18 through 21 is the human population, then the *threshold stability properties* represent measures of *human sustainability* for the ecosphere.**
The measures of resources directly consumed by humans are the dependent variable critical factors (DVCFs) of the independent variable critical factors (IVCFs) measured at the control points. The IVCFs can be impacted by feedbacks of the human loads (i.e., IVCFs pulled out of nominal by human load rates) and by disturbances (i.e., expected and unplanned events). Thus, the stability of the BLSS is dependent upon the stability of the human resource DVCF when the IVCFs are impacted. BLSS developers can perform analyses to predict how feedbacks from human loads and impacts from disturbances uniquely and commonly affect IVCFs. BLSS developers can then perform computer simulations and physical tests to see how the classes of selected load feedbacks and disturbances affect any given IVCF (while controlling for the other IVCFs), and how the affected IVCF impacts the particular human resource DVCF produced by the BLSS. Values of the human resource DVCF prior to disturbance/loading (X1/Y1), immediately following disturbance/loading (X2/Y2), and at a later time following disturbance/loading (X3/Y3) are then used to calculate resistance, resilience, consistence, and persistence. Using this Sustainability Assessment Framework, values of these four properties of sustainability can be calculated for the worst-case scenario of each class of disturbance and load feedback for each BLSS.	***Threshold loads* and *threshold disruptions* apply to DVCFs.** When the critical factor resource that is being *loaded* or *disrupted* is a resource at a control point that is further back in the network from the resource directly consumed by humans, the critical factor resource at that control point is called an IVCF. The DVCF is affected by a cascade of the disturbance (*load* or *disruption*) through the network from the disturbance point at the IVCF. Each *load* and *disruption* scenario of the IVCF could result in either a *load* or a *disruption* of the DVCF. The type of threshold impact on the DVCF is what determines whether the scenario applies to measuring *threshold load stability* or *threshold disruption stability*. For this reason, IVCF *load* and *disruption* scenarios should be selected based on resulting in either *threshold loads* or *threshold disruptions* on DVCFs. The *load* or *disruption* could still be directly applied to the human consumption resource (e.g., an increase in human consumption rate). In this case, there is just the critical factor of the resource consumed by humans, so there is no dependency upon an independent impact to a critical factor back in the network. There is no cascade to trace through the network from an IVCF to the DVCF. The modeling of the stored and throughflow available work energies of the entire network for the pre-disturbance and post-disturbance conditions can be performed as instructed in Jørgensen (2012, pp. 213–239) and Jørgensen et al. (2016, 89–103). The values of stored and throughflow available work energies can be in terms of power per unit area, mass per unit area per unit time, or other form of exergy unit equivalence.
The effect of variance on the sustainability calculations of a BLSS is being controlled by normalizing the stability properties to those of an equivalent (in bioregenerative aspects) Earth environment that is affected by variance. Any influence of variance on the X3 and Y3 critical factors of persistence and resilience, respectively, would be assumed to be in play in both the BLSS and Earth model environment(s). Thus, their influence on the calculations is controlled in the normalization. The word terraform is used for the normalized properties considering the calculations are developed on the basis of Earth sustainability; thus, any BLSS that achieves terraform specific stabilities of 1 has effectively terraformed the human habitation supported by the BLSS, making it as sustainable as an equivalent system on Earth.	**The Earth model to be used as a normalizing comparison to the ecosystem network in space in Eqs 22 through 25 of Table 8 should have IVCF control points that can be compared one-to-one with the IVCF control points of the space ecosystem in terms of the actual resource being disturbed for the calculation of DVCF *terraform specific stability properties* to be valid.** The number of producer nodes of the resource and the species/agents of producer nodes can be different between the space ecosystem and the comparative Earth model. The ratio of *threshold stability properties* should be done for the worst-case values determined for the space ecosystem and Earth.
The human sustainability of a BLSS is defined to be the stability of the human resource DVCF produced by a BLSS in response to human load and disruption impacts on IVCFs at the environmental control points of the BLSS and its ecosystem services network.	**The *human sustainability* of the ecosphere is defined to be the lowest values of the calculated *terraform specific stabilities* of the human consumed resources under *threshold loads* and *threshold disruptions* in response to selected *load* and *disruption* scenarios on critical factors at control points in the ecosphere. *Terraform specific stabilities* are normalized with values closer to 1 having greater *human sustainability*.**

1900 W *per capita* of additional solar and non-solar power is also required for powering *augmentational* growth.

For a human base or settlement that is only powered by solar insolation, N_{NSP} would be zero. The implication is that the area of solar panels in use will need to mathematically square as the distance from the Sun to capture the same amount of power. Table 10 provides examples of the same four locations but for solar-power-only settlements, providing the ratio of solar power panel area to land area under use. These examples reflect that it becomes exponentially more difficult to sustain a human base or settlement with just solar insolation further out from the Sun.

There comes a point of unsustainability where the required area of solar power panels is not feasible. At such a point, non-solar power generation as provided in the first examples would be needed. Non-solar power generation would be limited to geothermal, biofuel, chemical fuel, or nuclear fuel. With the exception of geothermal that requires a geologically active planetoid, the need to refuel would require local *in-situ* resources or a supply chain. The availability of *in-situ* materials in space is discrete and limited. Calculations indicate there is insufficient hydrogen available to collect with a scoop while underway to maintain power by nuclear fusion (Mauldin, 1992, Section 4.9) once efficient fusion power technology is available. Human bases and settlements would be limited to locations at planets, dwarf planets, asteroids, and Kuiper Belt objects. Travel and supply chain shipments between such locations would be at great risk.

4 Conclusion

The theory and the scientific development that backs the theory point to the need for a *self-restoring basal* ecosystem for *human sustainability*. The theory and the scientific development also point to the characteristics of an *augmentational* ecosystem that require the *basal* system to be developed sustainably. Both *propositional antecedents* and the nine *conditionals* of the theory provide a basis for a definition of sustainable development in space. A consistent definition of

TABLE 10 Comparison of settlement types at four Solar System locations. For mixed-power settlements, N_{NSP} (the ratio of non-solar power availability per unit area of terraformed area to the natural power available to Earth ecosphere per unit area) increases toward the natural power available to Earth ecosphere per unit area (334 W/m²) when there is only as much area of solar power panels as there is land area under human use (N_{SPA} = 1). Non-solar power becomes much more vital as distance from the Sun increases. For solar-power-only settlements, N_{SPA} (the ratio of solar power panel area to land area under human use) increases exponentially with distance from the Sun in cases where there is no non-solar power available for use.

Mixed-power settlements	Solar-power-only settlements
Mars:	
$2 \leq \left[\frac{1.02((1)(0.33)+1)}{1-N_{NSP}}\right]^{\frac{1}{2}}$ $N_{NSP} \geq 0.66$ $P_{NS} \geq 220\, W/m^2$	$2 \leq \left[\frac{1.02((N_{SPA})(0.33)+1)}{1-0}\right]^{\frac{1}{2}}$ $N_{SPA} \geq 8.9$
Asteroid Belt:	
$2.2 \leq \left[\frac{1.02((1)(0.33)+1)}{1-N_{NSP}}\right]^{\frac{1}{2}}$ $N_{NSP} \geq 0.72$ $P_{NS} \geq 240\, W/m^2$	$2.2 \leq \left[\frac{1.02((N_{SPA})(0.33)+1)}{1-0}\right]^{\frac{1}{2}}$ $N_{SPA} \geq 11$
Jupiter:	
$5 \leq \left[\frac{1.02((1)(0.33)+1)}{1-N_{NSP}}\right]^{\frac{1}{2}}$ $N_{NSP} \geq 0.95$ $P_{NS} \geq 317\, W/m^2$	$5 \leq \left[\frac{1.02((N_{SPA})(0.33)+1)}{1-0}\right]^{\frac{1}{2}}$ $N_{SPA} \geq 71$
Saturn:	
$7 \leq \left[\frac{1.02((1)(0.33)+1)}{1-N_{NSP}}\right]^{\frac{1}{2}}$ $N_{NSP} \geq 0.97$ $P_{NS} \geq 324\, W/m^2$	$7 \leq \left[\frac{1.02((N_{SPA})(0.33)+1)}{1-0}\right]^{\frac{1}{2}}$ $N_{SPA} \geq 142$

"sustainable development" with a comprehensive set of indicators and analysis tools are currently lacking in the space industry (Maiwald, 2023). Stated simply, sustainable development of a human settlement requires a *basal* ecosystem to be present on location with *self-restoring order*, *capacity*, and *organization* equivalent to Earth. The sustainable development of the human systems then becomes an *augmentational* activity that must proceed in a manner that does not produce unrecoverable instability in either the *basal* or *augmentational* portions of the total ecosphere. This follows the arguments for strong sustainability (Pelenc et al., 2015; Maiwald, 2023).

Establishing a settlement in a location with pre-existing *self-restoring order* and *capacity* equivalent to Earth appears to be impossible. For the *dissipative structures conditional* required for *self-restoring order*, 1) there is not a known planetary body in our Solar System that has a 1-g gravitational field equivalent to Earth and 2) humans are unable to artificially generate a conservative gravitational force field to establish *self-restoring* gravitational heat engines anywhere in space. Keep in mind, the other functions of *gravitational dissipative structures* needed for a *basal* ecosystem equivalent to Earth would also need to be naturally present (e.g., radiation protection). There is also research that suggests that even with a 1-g gravitational field, the very specific gravi-dynamics of the Earth-Moon-Sun gravitational system might be required for the biochemical and biophysiological metabolic processes of Earth life to function properly (Thorne, 2021). For the *power conditional* required for *capacity*, 1) there is no planetary body on our Solar System that has the diurnal cycle equivalent to one Earth-day and simultaneously 2) has a level of direct solar insolation equivalent to Earth.

These challenges suggest that even *level 3 sustainability* as modeled by the theory is not achievable. However, the solution might be in using balanced sustainability (Maiwald, 2023), an approach of partially replacing the non-critical functions of natural capital with technology. In an Earth-based context, replacing gravity and the magnetic field of Earth that both provide critical functions with technology would not even be considered. In the space context, the need noted in the previous paragraph is to replace elements of the *basal dissipative structures conditional* with technology and enhance the *basal power conditional* with technology, all considered as critical functions. However, certain configurations of ecosphere design in space might allow such a technological approach and still achieve *level 1 sustainability*. The science behind the theory suggests the key. An entire cross section of the ecosphere at some point in the exergy throughflow must be *self-restoring*.

Consider first what would be required to replace the Earth functions provided by *gravitational dissipative structures* with technology. Humans would need to develop *augmentational* technological systems to emulate Earth gravity and the diurnal solar insolation of Earth. The current methods under consideration in the literature are by using rotation to emulate gravity and solar power collection cells to collect solar power and then direct this power to LED lighting and control systems that emulate Earth-levels of solar insolation in a diurnal cycle. It is possible to emulate the apparent-weight effects of gravity using technology such as an O'Neill cylinder or a McKendree cylinder. What could be more challenging than designing a rotating cylinder that is the size and scale of a biome-sized land area on Earth? Designing technology that would generate the atmospheric pressure gradient as exists on Earth, the phenomenal effect of gravity and the normal force of the lithosphere on the atmosphere.

The spin of a cylinder around an enclosed atmosphere suspended in the free fall of space would not produce this pressure gradient without something to impart an angular velocity to the air suspended within the cylinder. One might imagine a complex system made up of air-columnizing structures that generate the needed angular velocity and a resulting apparent centrifugal force to push the air toward the outer ring of the cylinder as the cylinder rotates, creating an apparent weight effect on the air and resulting in an air pressure gradient. Such an internal structure would result in internal air friction on the spin of the cylinder, which would require energy input to keep the cylinder spinning at the required angular velocity to maintain the apparent centrifugal force equivalent to Earth gravity.

Herein lies the challenge: the technology used to generate the rotation, and therefore apparent weight and the air pressure gradient, is non-self-restoring. It is driven by *augmentational* technology in the form of irreversible forced heat engines. As noted earlier, high-power-density, forced-cycle heat engines are much less efficient than *basal self-restoring* heat engines driven by *basal* gravity and electrochemistry. In addition, the spinning system and its drive engine would be subject to maintenance, wear, and ultimate failure, requiring repair and replacement. Similar considerations apply to the technology to emulate the latent heat of formation of Earth for minimum ground temperature maintenance and tidal, the gravi-dynamic tidal forces of the Sun and the Moon on Earth, and the Earth magnetosphere for shielding the ecosphere from the solar wind. The use of material shielding solutions in space would not necessarily require a power supply. However, if an electromagnetic shielding system is used in space, this power requirement would need to be included.

What remains to be considered for providing the *self-restoring* anchor are the *electrochemical dissipative structures* of the biosphere portion of the ecosphere. Theory suggests that the *self-restoring* cross section of the *dissipative structure* network might be shifted to the *basal* ecosystem biological cycles that are driven by *self-restoring* electrochemical heat engines, Figure 5. The concept is that the *gravitational dissipative structures* being provided by technology become an extension of the *augmentational* systems that humans maintain, driven by the *self-restoring electrochemical dissipative structures* of the biosphere.

There is also the challenge suggested by the theory of an inability to maintain *basal* and *augmentational functional diversity* on location in space due to area limitations, thus limiting such an area-limited space ecosphere to *level 3 sustainability*. Such a result can be mitigated by utilizing a supplemental supply chain for an ongoing managed migration of new species and material from Earth (and other locations in space) to replace the ones that locally go extinct (depleted). This includes non-renewable energy resources (e.g., methane for chemical power; uranium and transuranic minerals for nuclear fission power; hydrogen, helium, and lithium for nuclear fusion power) needed to supplement the

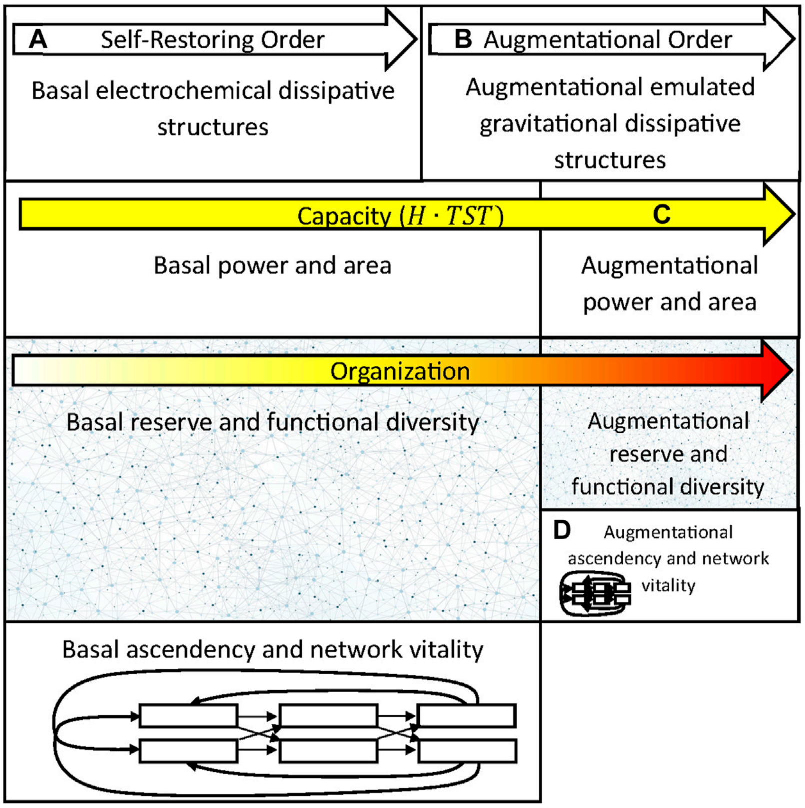

FIGURE 5
A balanced sustainability approach. **(A)** The *self-restoring electrochemical dissipating structures* of the basal biosphere are effectively shifted to start the *dissipative structure* network. **(B)** The *augmentational* ecosystem is then used to maintain the non-self-restoring technology needed to emulate the *gravitational dissipative structures* at the end of the *dissipative structure* network. Resources generated from the *basal* ecosystem must be utilized by ISRU and manufacture by ISMF into consumables, replacements parts, and full replacements units as needed to sustain the operation of the *augmentational gravitational dissipative structures* indefinitely. **(C)** More *augmentational capacity* is provided with technology being used to convert the available solar power at location as well as the exergy of biofuel and nuclear fuel into emulated Earth-level diurnal solar insolation and emulated gravitational power. **(D)** The concern is that if excessive biofuels are used for power generation, this could contribute to *augmentational ascendency* to an extent that it pulls the combined network outside of the *window of vitality,* resulting in excessive combined *ascendency*.

renewable resources when required to meet the *basal power conditional* and technologically replace functions of Earth *gravitational dissipative structures*. However, achieving higher *levels of sustainability* is not possible with such an ongoing supply-chain influx of species and material unless transportation between the settlement, Earth, and other locations in space that can provide resources becomes commoditized and ubiquitous, such that single-point disruptions of transportation do not shut down all migration and commerce. Such a wide-area network of intra-supportive ecospheres with a commoditized space supply-chain market could effectively solve the area problem. Ultimately, the question is whether a location in space can be sufficiently bootstrapped until it reaches the point of being internally *self-restoring*.

The theory provides interesting insights into ongoing human endeavors in space. The first concerns the plans of the member states of the International Space Exploration Coordination Group (ISECG) for the planned permanent human presence on the Moon (ISECG, 2020; Landgraf, 2021; NASA, 2021). The plans achieve less *human sustainability* than a space station in LEO. With a greater distance to cover for emergency egress, the escape plans are no better than those for a space station in LEO. The plans are heavily dependent upon a very limited *augmentational* supply-chain support system with effectively no *augmentational reserve* elements. Any attempt to use bio-mimetic or eco-mimetic technologies to provide human life support with bioregenerative capability that would be weakly self-restoring outside of Earth gravity only increases the supply-chain support needs due to the increased maintenance requirements of technology that integrates biotic elements. ECLS systems with redundancy somewhat mitigate the risk, but an *augmentational reserve* as a backup to the main and redundant ECLS systems would provide mitigation against the risk of redundancy failure, which is known to happen with *augmentational* systems (e.g., Krisher and Koenig, 2023). This is an understandable first step toward developing greater *levels of sustainability* over time. What is hopeful is that longer-term plans will be developed that consider incorporating more elements toward achieving *human sustainability*.

The second insight is that establishing a human settlement on Mars would be challenging to achieve any *level of sustainability*. *Level 4 sustainability* is ruled out by the distance of Mars from Earth. *Level 3 sustainability* and above is challenging due to the difficulty with a balanced-sustainability approach of developing a technological system to *augmentationally* produce the apparent weight and atmospheric pressure gradient needed to generate1-g *gravitational dissipative structures*. Even if one could develop and build the technology, the functional operation of a settlement on a city-size centrifuge table is difficult to conceive.

The third insight is that abductive, ontic, and ontological reasoning regarding our search for other life in the universe suggests that this theory is applicable to any life evolved anywhere in the universe driven by universal laws. It suggests one of many possible answers to the Fermi paradox. Perhaps we have not yet been visited by alien life due to the challenges any evolved life form would have associated with sustainability of that life far from its home star.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Author LI is on the Board of Directors of Norfolk Institute LLC which operates as a non-profit entity.

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspas.2023.1081340/full#supplementary-material

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