Is the human race sustainable?
Applying a material cycle approach to understanding the evolution and survival of our biological species

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Introduction

The “stable existence of the human race” is an important target for the current and the future generations of humankind. With limited resources and environmental capacity, the supply of food, water, materials and energy is being stretched but the population is still growing and economic development proceeds even faster. Natural disasters, pandemics, poverty, warfare, terrorism, pollution and global climate change could kill a tremendous number of people in our unpredictable future. Enormous effort is being devoted to preventing, avoiding or minimizing these risks. In considering all this, we must ask: can the human race exist stably on the earth?

The harmonious ecosystems we see throughout the world today have been maintained for a long time (probably millions of years or longer) with all the biological species, from algae to apes, adapted precisely to their environment and living in balance with each other for generations. By studying this harmonized system, we can understand some interesting features of the sustainability of species. If the human race is to survive sustainably, eventually an environment needs to be formed that includes all the other species and maintains a balanced cycle of energy and materials.

The human race cannot yet be considered to be an established species because its population continues to expand and increase its consumption of energy and materials. When considered in the history of the evolution, the problem is to evaluate whether the human race can eventually form an established species for an extended period, where these time periods are determined by evolutionary timescales that equate to that of generations. The assertion that the human race is still developing can be justified with the speculation that the existence of a species for a sufficiently long period (through a large number of generations) with a relatively stable population is a necessary condition for stable existence. The human race seems to be a long way from achieving such a state.

The human race can only achieve sustainability through a unique historical process that can occur only once in the history of earth. The failure to achieve this state will ultimately result in the human race’s extinction. As a result, the exact conditions involved cannot be reproduced and so this problem may not be answered through the use of regular scientific methodology supported by experiments and evidence with reproducible facts. Metaphor, imagination, simplification and other methods not regarded as "scientific" may have to be used to shed light on this issue. Many of the examples and simplified models we have used to analyze the activity of species in the context of evolution are not verified but very often observed and taken for granted. Here, using these methods, we will attempt to investigate the sustainability of the human race.

Stable systems

From an engineering standpoint, the activity of organisms on earth can be viewed as the flow of energy and materials. Species – or groups of organisms that convert and transfer material and energy – are the basic components of the system. In this paper, the apparent material and energy flows of a system are considered to develop necessary conditions relating to the establishment of a species. To simplify this analysis, genetic similarity or difference, which is one of the most important biological features, is neglected.

All of the known established species on earth have achieved a steady state of the flow that circulates in the environment. If we define the environment as a system (S), where there are inputs (I) and outputs (O), the temporal evolution of the system can be described by the equation:

$$dS(t)/dt=I(t)-O(t) \quad (1)$$

where t represents time and d/dt the temporal derivative. The steady state of the system is one where there is no change in time, that is to say dS/dt=0. Therefore, for a steady state:

$$I(t)=O(t) \quad (2).$$

Though this system can be described as steady, it is not necessarily a condition for the system to be stable as the amount of input to the system could be always increasing in time. Such a condition is not possible to maintain. Therefore, for a system to be stable, the temporal derivative (d/dt) of Equation 2 must be considered. This leads to the following equation:

$$dI(t)/dt=dO(t)/dt \quad (3).$$

It is clear that Equation 3 can be derived from taking the temporal derivative of Equation 1 and assuming that the rate of change in the system to be zero, that is:

$$d^2S(t)/dt^2=dI(t)/dt-dO(t)/dt=0 \quad (4).$$

These two conditions (shown in Equation 2 and Equation 3) provide the basis for the mathematical constraints for a stable system. To fully develop the necessary conditions for a stable system, the timescales of interest in this paper have to be considered. The current

Equations 2 and 3 require the first order and second order temporal derivative of S(t) to disappear, therefore, there can be no change to the system however short the timescales being investigated. This is too constrictive for studying the evolution of a species, a process that happens over timescales that are much longer than the lifetime of individual members of that species. Therefore, the derivatives (d/dt) of the above equations need to be changed to differences (Δ/Δt), where the timescales used are comparable to the lifetime of a single member of the species. Through this, short-term variations are allowed but long-term variations would imply that the system is not stable. Therefore, we now have:

$$\Delta I(t)/\Delta t=\Delta O(t)/\Delta t \quad (5).$$

Using these equations, it is now possible to gain some understanding about what a stable system is. Equation 2 shows us that, over the timescales of interest for these systems, there is no increase or decrease in the amount of materials or energy that a system holds. Further to this, Equation 5 shows us that there is no change in the throughput of the system over the timescales of interest. Therefore, when we look at an organism (or its group) as an element of the environment that takes materials and energy and exhausts the same amount, the flow should be roughly described by these equations. So even with the short-term variations in the population of a species, over a long period of time we can see that the species (or its group) is part of a stable system. On the contrary, if a system does not satisfy these equations, it cannot be considered stable. Equations 2 and 3 do not have to be applied only to living creatures. Devices or machines, such as the internal combustion engine, or chemical equilibria can also be described with this simple form of equation (as illustrated in Figure 1).

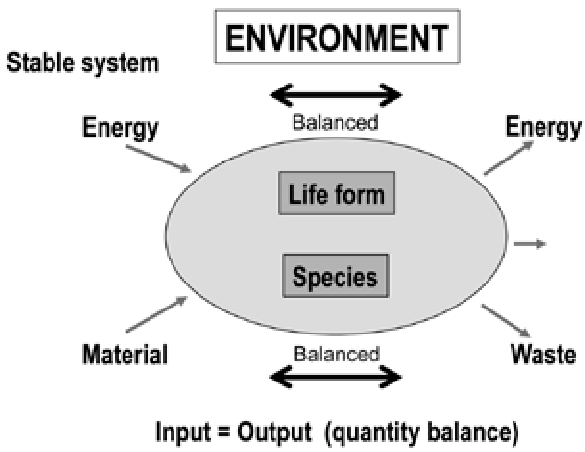

Figure 1. A balanced system in a steady state

The environment and the system

If we define the “environment” as a localized region where material and energy exchanges occur, then the “environment” discussed here is the one that can be completely reconstructed by the interaction of the organisms within it. The environment-organism system does not have to be a closed material and energy cycle but it should maintain a steady state of input=output in terms of material and energy balances and be a stable state where, over long timescales, the mean throughput of the material does not change. For this to happen, the environment must form a dynamic equilibrium with the living organisms through supplying materials and accepting waste. This concept is shown in Figure 2.

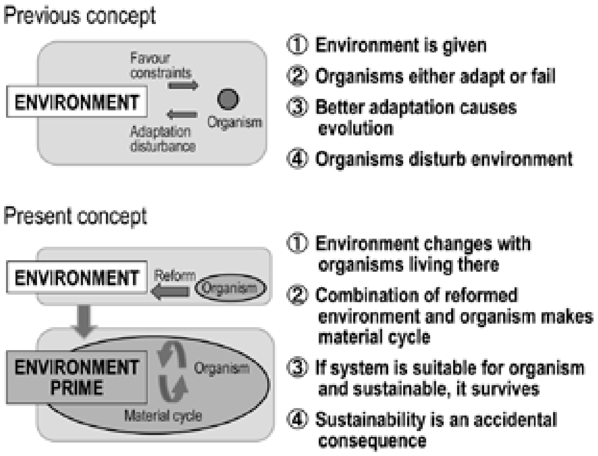

Figure 2. Two definitions of environment

Previous "traditional" concepts of nature and the environment supposed both to be unchanging. The human race has, therefore, come to be seen as a guilty party because it is always disturbing and destroying the natural world. But if we look at the destruction caused by human activity as a part of evolution, the concept presented here departs from the traditional understanding of humanity's place in relation to nature and the environment. An environment that hosts organisms is one that has been altered by the organisms it supports.

For instance, bare ground on the earth receives sunshine during the day and radiates its energy at night. If the ground is covered by plants, they absorb solar energy and convert it into their constituent compounds, while radiation to the night sky from the ground decreases. The stability requirement of the balance is kept when the energy absorbed from sunshine is converted or released to maintain a stable temperature. However, this results in a change in the energy flow and its balance point. The airflow, such as wind, would be different depending on the ground cover. Rainfall also changes the amount of moisture in the air and on the ground. Although the climate does not change, the environment experienced on the ground is different to that which existed before.

The environment-organism system is a flow of materials and energy between organisms and the environment. Many different organisms are involved in the environment and, as a result, they affect each other. The appearance or introduction of a new species to the environment inevitably changes the flow of materials as a result of the newcomer's activities. When new flow paths are created, only stable cycles with stable and balanced material and energy flow meet the criteria for survival.

Throughout the earth's history, a new balanced, stable and steady state of material flow arose whenever a new species was established. If we consider the effect of green plants, an atmosphere of 20 per cent oxygen and only hundreds of parts per million of carbon dioxide is a consequence of their photosynthesis. This has completely altered the atmosphere, which was dominated originally by carbon dioxide. This was one of the largest changes to the earth's environment and it took billions of years to happen. After that, the balance between photosynthesis and oxygen breathing has maintained a stable and steady state. Although not as large as this conquest by plants, the natural environment has significantly changed its material flow as a result of major changes to the organisms that dominate it.

Two species of animals, for example foxes and rabbits, maintain their material and energy balance as predator and prey with each playing a part in the other's environment. Energy and material (in this case sunshine and vegetation) flow from the environment to the rabbits, then from the rabbits to the foxes and, eventually, return to the environment. Material flow from grass to rabbits is controlled by the population of rabbits, which is limited by foxes, otherwise the vegetation might be completely eaten by the rabbits.

Natural systems, such as the grass-rabbit-fox material cycle, provide a feedback function to control the stability. When rabbits over-breed, the foxes can catch more rabbits and their population can increase. This results in predator-prey cycles, with the population of one species providing a feedback for the other. If such a system has reached a stable state then, when looked at over long timescales, the population of both predator and prey will be unchanging. This feedback process is a part of sustainability.

An organism can create an environment that is not necessarily suitable for the survival of that organism. A very simple example can be found in a bottle of wine. When fermentation begins, the environment inside the bottle is suitable for yeast to breed. However, the bottle soon contains alcohol as the byproduct of the yeast's activity. The resulting environment, which was made by the yeast, no longer allows it to survive. This is not sustainable because the material cycle is not completed.

A tree standing alone can be tested for its adaptation to the surrounding environment, including sunshine, climate and soil. From the classic Darwinist viewpoint, natural selection would affect this single tree. In the viewpoint presented in this paper, the tree receives sunshine and casts shade in which other plants, including the tree's seedlings, will have to grow while receiving less sunshine. The tree protects weeds from strong sunshine and prevents evaporation of water from the bare ground. The tree gathers rainfall and sends it to its roots. Its fallen leaves feed earthworms, which cultivate the soil by transporting air and minerals below the surface. This series of effects forms the systems observed in the local environment around the single tree. This system may eventually form a forest.

At the end of the process, the ground is covered by a wide range of plants, insects and an array of other organisms. The resulting system may or may not be suitable for the survival of the first tree that probably enjoyed full sunshine. This is a very different concept to seeing if the tree could adapt to the environment in which it was planted. This shows that what needs to be is evaluated is not the tree but the system that the tree forms with other organisms and the reconstructed environment they created.

Those who are selected to survive

Although the original concept of evolution was first proposed more than 150 years ago, its mechanism is still not completely understood. What this paper aims to stress is that selection, a matter of life or death for individuals or entire species, occurs through interaction with the environment. As was discussed in the previous section, this environment is not a wild, independent, solid environment but the byproduct of a strong interaction with the organisms living within it. It is true that what may seem like an external factor, for example the climate, may result in the death of organisms. However, the climate these organisms experience is actually an artificial climate, like the forest described in the previous section or a coral reef.

When the system an organism has created determines that organism's survival, it is the system – the combination of the organisms and their surrounding environment – that gets selected. As creatures unavoidably change the flow of material and energy as part of the system, this system itself is evaluated for its stability. This basically implies that a system will evolve continuously until it either reaches a steady state or destroys itself.

In classic Darwinist theory, changes in genes cause mutation and the resulting change in the body of a creature alters its ability to adapt to the environment or compete with other organisms. The best-adapted organism survives and the accumulation of this process causes evolution. In the original theory, the cause of variation was not identified but heredity and natural selection were sufficient to explain the change of the species or evolution.

Modern biology has found that Darwin's theory cannot be applied in some cases. The "selfish gene" theory, put forward by Richard Dawkins (1976), explains that selection works on the genes, where genes control the behavior of the organisms and organisms are regarded as only the vehicle of the genes. Genetic competition between individuals, groups and species can be observed everywhere.

Changes in the genes themselves are known to take place over a very long time with no preference for providing advantageous mutations. If we observe the apparent changes in environment and local material and energy flow, such changes occur relatively quickly. Where competition is observed, controlling the flow of material is regarded as the actual battle. The organisms that obtain a territory that enables them to control the flow of material and energy are those that have a better chance of achieving a sustainable cycle. Regardless of the function of the genes, actual changes in the material and energy flow system are important if the organisms are to form a sustainable system. Species and genes are biological concepts, whereas we can observe this sustainable material/energy flow. The difference between these two concepts probably arises from the difference between the thinking of biologists and that of energy scientists.

If the above consideration is correct, the observed appearance, prosperity, extinction and eventual evolution of a species are the result of significant changes to the material flow in the environment. An area that has a relatively large number of organisms (either fossils or living examples) and amount of mass shows considerable material and energy flow paths. This is particularly clear when we look at elements such as carbon, nitrogen and phosphorus, and the energy flow path from sunshine to various forms of chemical energy in organic compounds. Although the total may appear small when compared with the total abundance of these compounds and energy reserves on earth, the reconstructed local environment has material and energy flows for individual species that are significant and sometimes even fatal.

How beneficial or detrimental a set of material and energy flows is will be species dependent, allowing some species to thrive where others perish. However, the material flow, including the mass of the organisms, reaches a steady state once the species has become established. This is the observed evolution, when described from the material flow aspect.

Phase transitions, the logistic curve and material cycles

In phase transitions, there are no strong constraints on the system in the early stage so the growth is described by an exponential curve. Throughput of material also increases exponentially. Although the initial growth is similar to that of the exponential function, material and energy supplies become limited at some point and the growth slows down. This transition happens when approximately half of the environment is occupied by this newly growing phase because scarcity becomes a limiting factor. A stable state is then formed, based on the constraints of the environment. This is shown in Figure 3.

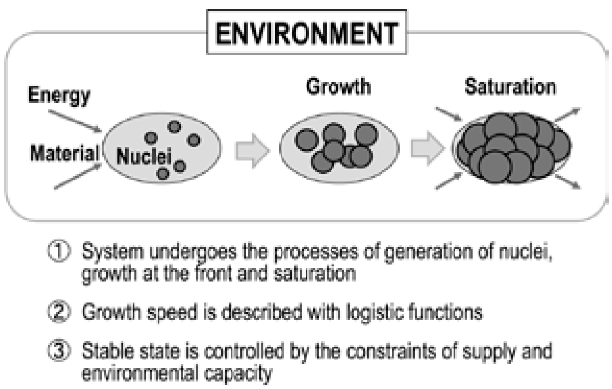

Figure 3. Model of speciation and phase transition

The kinetics of the phenomena described above can be described with a sigmoid curve called a logistic function, as shown in Figure 4. It should be noted that while the logistic function is often applied to population growth, application to the change of material cycle system in the environment is a new concept. The author considers this function would also be appropriate to describe the material supply aspect of the growth of a species because the population growth and the change in the material cycle result naturally from the interaction of species in their local environment.

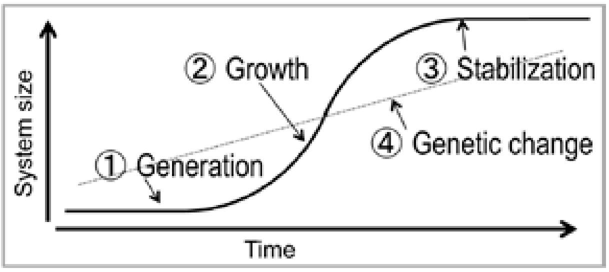

Figure 4. Logistic curve of system growth relating to the material balance quantity shown by the black line. The dotted line shows the system growth for constant genetic change

The generation of a species is often considered in relation to moving into new territories. A species can sometimes move from a territory where a material and energy cycle existed to another. This happens, for example, when creatures that lived in the ocean begin to live on land or when they start to be active at night. Such a change can be small at first and no major genetic variation is needed. However, the change opens up a new frontier for life and a niche may become available to the organisms where there is a relaxation of the constraints that previously applied. The first part of Figure 4 indicates such a generation of a candidate of new species.

It is often believed incorrectly, as represented by Thomas Malthus' population theory, that the initial exponential growth continues permanently. However, as the growth in population continues, the environment's limited resources (material and energy supply or capacity to accept waste) can create a limiting factor for growth and ultimately the throughput of the system. Therefore, the eventual growth of a new species in an environment slows down and finally stabilizes in accordance with its limitations, for example, area and food supply. It should be noted that this stable state cannot always be achieved because the reconstructed environment is not always suitable for the organisms. Also, we cannot predict what the dominant limiting processes are going to be.

The changes to a system described above mainly consider the material balance of a system and its relation to the development of a new species and ignore the impact of genetic change. Modern biology has revealed that changes in genetic structure occur at a constant rate as shown in the straight dotted line in Figure 4. These changes are neutral, so they do not necessarily create an advantage for an organism. Of course, genetic change is an inevitable cause of the generation of new biological species. However, change in the material cycle in the local environment, particularly in the growth of population, appears punctuated and intermittent. This disagreement suggests that the relatively rapid growth and change of the material cycle system does not correspond to the relatively slow and steady genetic change. It is after the stabilization of the population – where this "sustainable" status continues for a number of generations – that accumulated genetic changes would eventually separate the group of organisms from their parent species. Eventually, crossbreeding may become impossible, resulting in a new species.

Punctuated evolution with multiple species systems

The evolutionary process proposed here is driven by change in the material cycle of the environment, which is inherently intermittent. In a relatively short period of time change occurs to the entire group of organisms and the environment that surrounds them. This is followed by relatively long periods with an almost a steady number of organisms and material flow. All other unstable systems, which do not satisfy Equations 2 and 5, do not last long and disappear before they leave observable traces.

One piece of evidence for this punctuated evolution is fossil gaps. It is difficult to find a fossil of a species if a similar form of organism has not existed for a long enough period of time to leave a large number of identical bodies behind. For this long period to occur, the material recycle system has to be operating with a stable material flow that allows a species to establish itself. This mechanism supports the apparent punctuated equilibrium originally proposed by Gould and Eldredge (1972) and explains aspects of this theory from a non-biological perspective.

In Gould's and Eldredge's theory of evolution, biological species that have been observed through fossils exhibit a period of relatively fast change in genetic material and species-specific features. A much longer period with significant biological change is not observed. From the aspect of material cycle, the biological (and especially genetic) change may not be observed clearly. However, the material and energy flow paths and throughputs have made the transition from one equilibrium to another. These changes are illustrated in Figure 5.

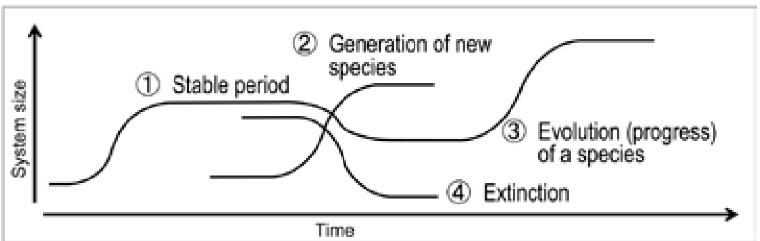

Figure 5. Punctuated evolution of multiple species considered from material cycle

In a multi-species system, the species interact by niche sharing, predation, competition and various forms of material and energy exchange in the local environment and the balance is maintained by delicate ecological mechanisms. However, maintaining this balance is not easy. Attempts by organisms to move into a new niche always affect the indigenous species. When an invader moves into a niche it can prompt the birth of a new species. If the new environment the invader creates is suitable, it starts a new material cycle system with exponential growth. This necessarily affects the indigenous species and their systems by plundering their territory, food and resources, regardless of whether the newcomer will be successful eventually or not.

Referring back to one of the previous examples, if a mating pair of foxes is washed ashore on an isolated island where rabbits are already enjoying a safe existence, the foxes would try to catch rabbits for their survival. If the foxes are good at catching rabbits, they will immediately breed and establish a territory that will fill the island. If they are too slow at catching rabbits, they will starve to death. However, if the foxes are too adept at hunting, the rabbits will eventually disappear and neither species will survive. The foxes and rabbits need to achieve a balance in their abilities if they are to survive sustainably in this newly formed system of predator and prey.

The process of creating a new material cycle through the foxes' invasion may change the lifestyle of the organisms involved. For instance, the rabbits may have to adapt their territory in order to survive. Such changes may then cause the rabbits' fur to change color or may lead to improvements in their hearing or running ability. These adaptations may eventually result in the formation of a new species. At the same time, the vegetation would alter significantly due to the decrease in rabbit numbers.

When a series of changes occurs to a material cycle system, a species can fail or even become extinct. However, another new organism would always attempt to fill the niche and, through this process, sustainable systems are established. Evolution is a series of relatively fast changes over a short period of time, followed by a long period of stability. This results in the observed punctuated equilibria. For biologists, the fact that there is only a small amount of fossil evidence of the evolution of a species presents problems for evolution theory. However, from the viewpoint of material throughput, it is a natural consequence of the very small quantity of material involved in this transfer phase compared with the amount available in the much longer state of stability.

The case of the human race

The above consideration can easily be expanded to analyze the case of the human race, at least as a candidate for becoming an established species. The human race has specific features that can be compared with those of other organisms. Our actions in the environment, our attempts to establish our material cycle system and our impact on the organisms around us are essentially the same as those of many other species in the history of evolution. From a material cycle viewpoint, it is obvious that the human race is not an established species because its population, lifestyle, material cycle system and throughput are still changing. Special attention should also be paid to the fact that the human race is increasing material and energy consumption per capita while other organisms maintain a material/energy throughput that is roughly proportional to the population. Even with a stabilized population, the human race will still be able to increase material throughput through technological development.

The territory and life zone of the human race has already spread all over the surface of the earth and is affecting a significant number of organisms. The development of agriculture and land use, in particular, has completely changed the appearance of the planet. According to statistics from the Food and Agriculture Organization of the United Nations, approximately 40 per cent of the earth's total land area is used for agriculture (FAO 2012). The vegetation that once covered the earth, converting atmospheric carbon dioxide to oxygen, has changed drastically through agricultural development. By using irrigation and fertilizer, the human race dramatically increased the material throughput from photosynthesis to human beings. The human race has used its intellect and other specific advantages to overcome natural constraints, expand territory and change the material transfer in the environment. However, there has been no concerted effort to use technology to stabilize the material flow in order to form a sustainable cycle system in the environment.

The speciation of organisms on earth – the human race included – can begin from the change of a life zone, by invading a new niche or simply by changing the food source. In the past, the human race has changed its lifestyle by migrating from forest to grassland, inventing agriculture and farming and using fire, tools and, later, machinery. These changes always caused an increase in material throughput and resulted in population growth. Relatively slower periods were observed in history, when technological growth was not significant. However, the ever-increasing technological improvements in recent history and changes in the social system have driven a rapid and continuous growth of material throughput, expansion of territory and life zone and population growth. This has not reached a steady state because constraints in the supply of various resources have been overcome by technological improvement, causing a significant increase in the material/energy throughput per capita.

It should be noted that through punctuated equilibria, as shown in Figure 5, the increase in the activity of the human race is almost always accompanied by the extinction of other species. This is unavoidable because of the limited resources and environmental capacity of the earth. These limits have not been completely resolved by the advance of technology. Many of the organisms deeply involved in the human material cycle system, such as agricultural products and livestock, are already a part of the unsustainable growth of human activity and equilibrium material and energy throughput cannot be expected to increase in this way forever. The human race is already in the latter half of growth shown in Figure 4 and our expansion will have to stop eventually.

The main idea discussed in this paper is that, to achieve sustainability, ie. prolonged survival as a species on the earth, the human race needs to develop a material cycle system in a steady state. However, this is merely one criterion necessary for survival: it is required to make the human population and surrounding biosphere stable and all material and energy throughput form a sustainable equilibrium. This is what we should aim for as a minimum requirement for stability.

Summary and issues for further consideration

Established biological species on earth have stable material cycle systems. To achieve a continuous and stable existence, the species must take in and consume a roughly stable amount of matter and energy from the environment and expel a similarly steady amount of "waste" or matter to the surrounding environment. This balance must be maintained over a large number of generations and is a minimal requirement for the sustainable existence of a biological species. On this basis, the human race has yet to – or may never – become an established species that can exist sustainably. The idea of "sustainable development" is a contradiction because the word "sustainability" seems to imply "development" or "improvement" as a desired state of human existence. However, continued development must, at some point, become unsustainable.

Based on evolutionary theories that consider the development and establishment of a species, the continued existence of the human race can be analyzed using a model that describes the stability of material flow systems. Biological species were able to establish a stable balance before the appearance of human beings. But these species were simply living lives limited by the material supply and environmental constraints that suppressed their growth. To establish a sustainable model for the human race – one that ensures its survival but also allows for the possible growth and improvement of living conditions and prosperity – will require additional consideration beyond this sustainability analysis.

The human race developed civilization and expanded its material and energy throughput with its population growth. However, we are already in the latter half of the sigmoid curve of development, where various constraints – such as material supply chain, environmental capacity to accept waste and a shrinking niche – will play a major role in stabilizing growth. These constraints are unavoidable and necessary to establish sustainability and guarantee human survival. However, if the human race is to continue its improvement beyond this stabilization, other mechanisms that allow the further progress of human activity with a sustainable material flow system are required.

As yet it is unclear if the human race will reach a steady, stable state that is sustainable. We may, like the pair of foxes on the rabbit-inhabited island, reach a state with a sustainable material cycle. This would allow the sustainable existence of humans as a species on this earth. However, like the tree that seeds the growth of a whole new environment only to find that it can no longer survive there, we might recreate our environment to such an extent that we can no longer survive. This would destroy our species but create an environment that allows a whole new class of species to thrive. We do not know what the outcome will be but, as a unique species that has used technological development to aid progress, we could use technology to ensure we become a species that establishes rather than destroys itself.

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