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# Global Warming: Is It (Im)Possible to Stop It? The Systems Thinking Approach

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**Abstract:** For some time, there has been a slow but gradual rise in the average temperature of the entire globe, a "global warming", in fact, the result of human and natural processes that have been producing this phenomenon for decades. Since they are not directly perceived by individuals, these processes and their effects have been ignored for a long time, or at least not considered to be immediately harmful and dangerous. Global warming does not depend so much on solar radiation as it does on the greenhouse effect deriving from the continuous emission, by human activities and natural events, of greenhouse gases that accumulate in the atmosphere and form a barrier to the dispersion of heat produced by solar radiation. A good number of models exists to explain how global warming is produced, which are technical in nature and consider the production of greenhouse gases as the most important cause; however, they do not always analyze and justify the reasons for such emissions. Following the logic, language and methods of Senge's systems thinking, the paper aims to present a general model, the GEAM—qualitative in nature, but rational and coherent—for highlighting the interacting factors that give rise to and maintain global warming. This model constitutes a reference framework to identify possible "strategic areas" within which to identify man-made "artificial" and "natural" factors that can control the phenomenon and to order the countless ideas and interventions that different nations carry out individually to control global warming. The model presented is qualitative in nature and does not allow immediate calculations or forecasts to be performed. However, it could guide in-depth scientific research in generating accurate forecasts and simulation using the tools of systems dynamics. In conclusion, understanding how global warming is created and if and how it could be controlled is the aim of this work. Finally, I want to note that the purpose of this work is not to analyze the technical aspects of the phenomenon of global warming, or to deepen the measures and actions to contrast it, but to provide a "general model of description and understanding" of the phenomenon using logic and language of the Systems Thinking Approach (according to Peter's Senge and Piero Mella), with the aim of highlighting three fundamental strategic areas for countering the phenomenon and four uncontrollable phenomena, triggered by global warming itself, which can make strategic control difficult. Furthermore, I highlight the role played by the world population, understood both quantitatively as a number and qualitatively as a level of economic development, in the production of global warming. Lastly, I observe how the different strategic actions that nations can, indeed must, implement to stem global warming are systematically interconnected and interacting; however, these interactions can produce unknown effects and consequences that must be carefully researched and evaluated—encouraged, if positive, reduced or eliminated if negative.

**Keywords:** global warming; climate change; greenhouse gases; GEAM; global economic activity model; albedo effect; Gulf Stream; thawing of the tundra



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## 1. Introduction

### 1.1. Physiological Temperature Control

Man has an innate tendency and vital need to "control" the variables whose dynamics cause problems, both in the domestic microenvironment and in the physical, biological and social macro-environment, when perceived using the means of observation available to man [1]. With the advancement of knowledge in the biological field and in medicine, man has learned to control even those variables that disrupt his physical and mental well-being and hinder the work to produce, in an organized form, the goods and services necessary to meet his needs and achieve his aspirations. This control, of course, concerns his vital biological variables, such as the energy to be acquired through food and water, the availability of tools for one to protect oneself against threats, to move in space (transport), to communicate, etc. Man must also control the dynamics of the variables he interacts with, both at the "active" level, by producing them, and at the "passive" level, by being subjected to them, when they constitute a danger to his existence, for example, the level of river waters, fires, threats from enemies, etc. Some of these variables have regular, predictable dynamics, others mutate irregularly and require effective control. The motto attributed to John von Neumann [2] is very clear on this; it identifies the variables that need control by identifying the nature of the processes that produce these dynamics.

> *"All processes that are stable we shall predict. All processes that are unstable we shall control . . . This was John von Neumann's dream"*. [2] (p. 182)

In simple words, "controlling the dynamics of a variable" means modifying its "trajectory" so that it can reach a given "target value", not exceed a "limit value", or respect a "constraint". Although the control process can also be very complex [1], it essentially develops as follows:

a. Specifying the objective (constraint or limit) that the variable to be controlled must achieve; if several objectives are to be achieved at the same time, governance must determine a "policy" that indicates the priorities and intensity regarding the achievement of the objectives.
b. Identifying other variables, *causally* connected to the one to be controlled, that man can modify with some known process to correct the one to be controlled. For this reason, they are called "control levers"; control is "multi-levered" when it is carried out by means of several levers at the same time. When control is multi-levered, the "manager" of the control system must identify a "strategy" that specifies *how many* and *which* levers to use and the *intensity* of use of each.
c. Measuring the "error", i.e., the "deviation" between the "target value" (or the constraint or limit) and the "actual value" of the variable to be controlled, i.e., [error = target value—actual value].
d. Acting on the "control levers", so that, depending on the extent of the error, they assume the values necessary to modify the variable to be controlled; the levers can be natural, physiological, automatic or voluntary, artificial, or in support of the artificial ones.
e. The process can also be repetitive, attempting to change the dynamics of the variable to be controlled in multiple, successive steps.
f. The control is successful when target value = actual value, i.e., when error = 0.

This process of correcting a variable as a function of the magnitude of the error with respect to the target value is the typical feedback control.

> *"We have thus examples of negative feedbacks to stabilize temperature and negative feedbacks to stabilize velocity"*. [3] (p. 97)

> *"So a great variety of systems in technology and in living nature follow the feedback scheme, and it is well-known that a new discipline, called Cybernetics, was introduced by Norbert Wiener to deal with these phenomena. The theory tries to show that mechanisms of a Feedback nature are the base of teleological or purposeful behavior in man-made machines as well as in living organisms, and in social systems"*. [4] (p. 44)

Among the many variables man must keep under control to survive, the most relevant is the temperature of the body around the normal physiological value, within the range of 35.5 °C–37 °C. The "distance" between the actual temperature at a given moment and the normal one of reference is perceived as being hot or cold, with all possible gradations; hot, cold, chilled, frozen, scalding, burning and boiling are the subjective terms used to indicate the extent of the "error" before an objective measurement is made. The "history of humanity" could also be interpreted as a continuous search for the "tools", that is, the control levers, to maintain a normal physiological body temperature.

The "automatic" physiological "levers" for the control of body temperature are the "chills" and "movement" to raise the temperature, or the "sweating and stillness" to lower it. If we run a race, the movement warms the muscles but sweating tries to cool them, pushing us to rest (second additional lever). "Voluntary" levers, often artificial, are used to supplement the physiological ones. If we are cold, we must increase the quantity and quality of clothing; if we are hot, we must gradually remove some clothing. Are we still hot or cold? Then, let us take shelter in a cave, in a stone, brick, or wood house, or one with heat insulation modules; we can light a fire in a fireplace, light a stove, buy an inverter air conditioner. The heat and cold are not yet under control using these levers? Then, we can resort to "extraordinary levers"; we can migrate to cool or warm environments; in summer, we take holidays in the mountains; in winter, in the Caribbean.

These elementary examples show why, over the millennia, we have gone from fires lit with dry branches in a cave to air conditioners in eco-sustainable skyscrapers, as well as how clothing has evolved, from animal skins to woven vegetable and animal fibers, even super-insulating synthetic fibers. This evolution in the levers and instruments of control also leads to an improvement of the quality of clothing, housing and tourism as well as an increase in their demand and production.

When the previous "control levers", which operate directly on the physiological variable of body heat, are not sufficient, it becomes necessary to implement an "exogenous-structural control" directly on the variables that "externally influence" the variable to be controlled. If the climate is so cold or hot that no "operating lever", physiological or artificial, is sufficient to cancel the "temperature error", one could try to modify the climate variables, thus implementing a "structural control" of the temperature of man's environment, the Earth. This lengthy premise is necessary to introduce the subject of this work, that is, investigating the control systems that can maintain an acceptably stable value of the temperature on Earth when it becomes "too low" or "too high" for the stability of our existence.

### *1.2. Ambient Temperature Control*

Throughout history, man has faced cooling phases on Earth, even including extensive and persistent glaciations [5] from which he has tried to defend himself by taking refuge in caves or, more often, migrating to less-cold sites, even if he has had to suffer famines that have placed his survival at risk [6,7]. Even today, in "cold" countries such as Canada, an attempt has been made to combat the cold by creating artificially heated underground neighborhoods. An example is Montreal, capital of Quebèc, referred to also as Reso; this area contains a system of about 33 km of galleries and underground tunnels—which cover about 3.6 million square meters—with shops, offices, hotels, banks, museums, as well as residential complexes and shopping centers to allow the population to live completely underground in winter [8–10].

Today, there is the opposite problem; a slow but gradual rise in the average temperature of the entire globe is occurring, a "global warming", the result of human and physical processes that have been acting for many decades. Since such processes are not immediately felt by individuals, they have been ignored for a long time, or, at least, identified as not immediately harmful. The gradual increase in global warming, perceived through adequate tools and accurate measurements [11,12], has begun to produce very serious effects on the ecosystem [13], to name but a few, "climate gone mad", melting ice (polar caps, glaciers, tundra), rising sea and ocean waters [14,15], estimated at 180 cm. in 2100 [16]; drought, the salinization and accumulation of salts in the soil leading to aridity, increased desertification; the alteration of fauna and flora; and many others. "*Therefore, global warming* *has impacts that extend to the hydrosphere, the cryosphere, the biosphere and the geosphere due to interactions and feedbacks between these systems*" [17]. Today, in communications and education, there is a tendency to abandon the term "global warming" for "climate change" [18,19], which refers directly to the manifestation of extreme "local" phenomena attributable to warming [20]—such as anomalous atmospheric phenomena, intense rains [21], sudden hailstorms, frequent floods, the increase in tornadoes and hurricanes [22], intense storm surges, peaks of heat and cold, etc.—rather than mentioning the overall average warming of the globe [17]. In fact, for most individuals, global warming is not directly perceivable because, at the planetary level, the temperature rises on average by a few degrees over several decades, while we can easily perceive the sometimes-devastating phenomena caused by global warming.

### *1.3. Objectives and Structure of the Paper*

To try to present a general picture of the factors that give rise to and maintain global warming and of the possible "levers" for controlling it—both at the "natural" level, which operates at the planetary level, and the "artificial" level, designed and applied by man—it is useful to build a model that allows us to understand the origin of the phenomenon and that constitutes a reference framework to identify possible control processes. I employ the methods, logic and language of "systems thinking", as popularized by Peter Senge [23], according to whom, to understand the dynamics of a broad reality, it is necessary to identify processes that cause this dynamic, looking for cause–effect connections among the variables and, above all, identifying the "circular bonds" ("loops") that result from their interaction. Although systems thinking is widely known, it is appropriate to provide a summary of it in Appendix A.

The paper is structured as follows: Section 2 presents Daisyworld, a simple model by James Lovelock, to demonstrate how the self-regulation of the temperature of a planet is possible in theory. This forms the basis for understanding the difficulties encountered in controlling global warming due to the presence of specific factors, which are examined in Section 3. Section 4 proposes a simple but effective model, GEAM, the Global Economic Activity Model, which describes the process that generates global warming. The global economic system and population growth are the two main factors that generate the production of greenhouse gases. The GEAM also makes it possible to identify some "strategic areas" our efforts must focus on to control global warming, thus identifying the possible concrete "measures" of the "human strategy" to be adopted. Section 5 suggests a "three-lever strategy", the "removal–consumption–production strategy", which can be implemented by governments but regarding which there is no unanimous consensus at present. The model is completed by combining the levers of the "human strategy" with a "natural lever", which would initiate an "automatic control" of global warming; this lever is represented by the slowdown of the Gulf Stream, caused by global warming itself, which could stop the warming effect in the North Atlantic land mass, possibly causing glaciation in the Northern Hemisphere; this is the subject of Section 6. Both the "human strategy" of control of global warming and the natural lever represented by the slowing down of the motion of the Gulf Stream must consider some negative factors generated by global warming itself, which produce harmful reinforcing loops that further increase warming. This issue is addressed in Section 7. Conclusions and suggestions follow.

*Note*: Preferring to directly present the thinking of the authors cited without imposing my own interpretations, I include a wealth of quotations in my paper. I did not want to, nor could I have in such a specific work, insert even a brief literature review.

## 2. James Lovelock's Theoretical Model of Planetary Thermo-Regulation: Daisyworld and the "Albedo" Effect

### *2.1. GAIA and Daisyworld*

It is useful to present an initial model that shows how we can conceive a "natural" control process that operates at a planetary level to ensure that a suitable temperature can be maintained, since an increase in the population of the Earth's biological species can suffice to modify temperatures [24]. Lovelock names this fantasy planet Daisyworld, where only "masses" of black and white daisies live. Daisyworld is a metaphor proposed by James Lovelock in *Gaia*, his major work (containing contributions by the biologist Lynn Margulis). This work shows that the earth is a single evolving system where a multitude of interconnected physical and biological variables exist, which can, in principle, be considered an evolving "living being" and which maintains itself in equilibrium over time through a control system made up of a set of reinforcing and balancing loops operating on a planetary scale. This system works thanks to the variation in the masses of daisies which, of course, are not aware of the functioning of the control system to which they belong. This is how Lovelock explains the origin of the term "Gaia", which he used to represent a system capable of self-regulating its climate.

> *"An entity comprising a whole planet and with a powerful capacity to regulate the climate needs a name to match. It was the novelist William Golding who proposed the name Gaia. Gladly we accepted his suggestion and Gaia is also the name of the hypothesis of science which postulates that the climate and the composition of the Earth always are close to an optimum for whatever life inhabits it"*. [25] (Online)

The Gaia's hypothesis postulates a land in which climate and chemical composition are constantly stabilized in a form conducive to life, thanks to the incessant interaction between living beings and their environment. The notion that the earth was a living system of some kind has a long history and the choice of the name Gaia for this hypothesis is due to the recognition of the first literary references in classical Greece. ([26] (p. 207)).

> *"I failed to make clear that it was not the biosphere alone that did the regulating but the whole thing, life, the air, the oceans, and the rocks. The entire surface of the Earth including life, is a self-regulating entity and this is what I mean by Gaia"*. [27] (Preface)

> *"Lynn Margulis, the coauthor of Gaia hypotheses, . . . in 1979 she wrote, in particular, that only homeorhetic and not homeostatic balances are involved: that is, the composition of Earth's atmosphere, hydrosphere, and lithosphere are regulated around "set points" as in homeostasis, but those set points change with time"*. [24] (Online)

Lovelock presents Daisyworld, a hypothetical simplified world-ecosystem, on which only two populations live that, by self-regulating their masses as the global temperature of the ecosystem changes, control the planet's global warming dynamics, indefinitely resisting the limited random variations in heat emitted by the star (the equivalent of the sun). More specifically, Daisyworld is thought of as a world covered with daisies (element of fantasy), exclusively white or black, which form two distinct masses (populations) whose color gives them opposite survival characteristics. The *white* daisies are suitable for warm climates, as the white color allows them to reflect a good part of the sunlight that hits them, thereby avoiding dying from being roasted; the *black* daisies, on the other hand, are suitable for cold climates, as their black color retains much of the sunlight, thus providing them with the energy to avoid dying from being frozen.

### *2.2. The Automatic Control System of Global Warming in Daisyworld*

Using the language and symbolism of systems thinking (Appendix A), it is easy to demonstrate that Daisyworld can maintain its thermal and biological balances thanks to the joint action of two "balancing loops", which guarantee thermal equilibrium, as indicated in the model in Figure 1.

The control system in Figure 1 includes only the following variables:

1. *Intensity of solar radiation*: this is an exogenous, uncontrollable variable; Lovelock did not provide any obstacle to radiation or any barrier to the reflection of light.
2. *Temperature of the planet*: this is the variable to be controlled (kept under control), whose dynamics, in case of variation with respect to an equilibrium temperature due to greater or lesser radiation, must be modified and brought back to the equilibrium value.

3. *Mass of daisies*, black and white: these represent the control levers that act on the temperature in Daisyworld through the size of the albedo effect, which depends on the masses themselves.
4. *Dynamics of the mass of white daisies*: since they live well in a warm environment, when the radiation becomes more intense and the planet warms, they multiply and increase in number; the opposite dynamic, contraction, manifests itself when the planet cools.
5. *Dynamics of the mass of black daisies*: since they live well in a cold environment, when the radiation becomes more intense and the planet warms, they die and their numbers diminish; the opposite dynamic, contraction, manifests itself when the planet warms.
6. *Albedo effect*, or reflective power; this expresses the percentage of incident sunlight on the planet that is reflected in all directions, thereby preventing warming (to a certain extent); therefore, it represents the variable that allows temperature to be controlled. The magnitude of the albedo effect *depends* on the extension of the masses of daisies, according to the two loops in the model.
7. Loop (**B1**): the *white daisies* reflect light; the greater their extension, the greater the albedo effect. Sunlight is reflected and this hinders heating, causing the temperature to fall.
8. Loop (**B2**): the black daisies do not reflect light, thus retaining heat; the greater their extension, the less sunlight is reflected and the more the temperature rises.
9. In the event of an increase in temperature, the two loops produce a joint action, as shown below (the case of a decrease in temperature is just as easily represented, with appropriate adaptations).

Loop (**B1**):

[1.1] + radiation = + temperature → + white daisies → [*same* direction of variation, "**s**"]
[1.2] + white daisies = + albedo effect [*same* direction of variation, "**s**"]
[1.3] + albedo effect → - warming = + temperature reduction [*opposite* variation, "**o**"]

[*End* of Loop [**B1**]. Repeat]

Loop (**B2**):

[2.1] + radiation = + temperature → - black daisies → [*opposite* variation, "**o**"]
[2.2] - black daisies = + albedo effect [*opposite* variation, "**o**"]
[2.3] + albedo effect → - warming = + temperature reduction [*opposite* variation, "**o**"]

[*End* of Loop [**B2**]. Repeat]

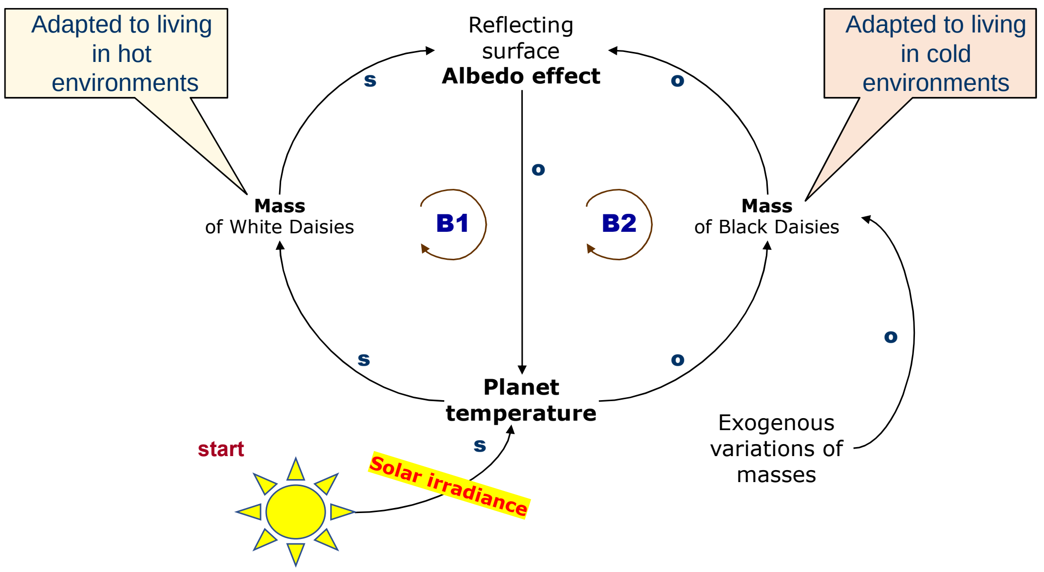


**Figure 1.** Metaphor of Daisyworld and process of self-regulation.

The choice of black and white daisies was necessary to highlight their role in producing the albedo effect; models have also been developed in which black and white daisies have been replaced by masses of grey daisies, but these models are not very effective. As much as the model in Figure 1 seems innovative and, in a sense, striking for its effectiveness and simplicity, in fact, "there is nothing new" in it; it simply describes a "two-lever" control system completely analogous to the one that explains how to regulate the water temperature of a tank using one tap to open or close a flow of cold water (mass of white daisies) and one for hot water (mass of black daisies). However, there is a substantial difference between the Daisyworld and bathtub models; in the latter, the user of the regulation system sets the temperature target and adjusts the water flows to achieve and maintain the objectives, while the Daisyworld model appears as a system that self-regulates the two populations of daisies; the regulation of the planet's temperature appears as a consequence of this self-regulation.

*Note*: Lovelock's model also allows for simple numerical simulations [1,28] and analytical developments [29] regarding the dynamics of the masses of daisies and the temperature of the planet. However, such simulations require that the functions determining the variations in the interconnected variables be specified.

## 3. Why the Daisyworld Model Is Not Applicable to Earth

### *3.1. Structural Differences between Daisyworld and Earth*

The Daisyworld metaphor seems adequate in an ideal world, but we must ask ourselves if it would be effective if applied to Earth; would there be any possibility of natural self-regulation? The answer is "no". Focusing on the continuous increase in global warming, it is unrealistic to think that there are simple natural mechanisms that can automatically counteract a warming phenomenon that has lasted for several decades, although, as we see below (Section 6), the possibilities of glaciation are not to be excluded. Therefore, limiting ourselves to the *increase* in the temperature of the planet, we immediately notice some fundamental differences between the modus operandi of Daisyworld and the Earth.

*Factors that provoke an increase in temperature*: In Daisyworld, it is assumed that the temperature changes solely because of the changed intensity of the sun's irradiation. On Earth, the irradiation of the sun warms the planet, but the intensity remains constant; the temperature is affected by human activity and natural phenomena, which are not foreseen in Lovelock's model.

*Greenhouse effect*: In Daisyworld, no greenhouse effect is considered; if solar radiation heats up, the albedo effect reflects the rays, thereby reducing heating. On Earth, as we know, things are different, because human activity, together with natural phenomena, produces "greenhouse gases" that hinder the reflection of the sun's rays; therefore, heat is trapped in the atmosphere, raising the temperature of the planet (Section 7).

*Black and white daisies*: In Daisyworld, the masses of daisies are the "control levers" that modify the albedo effect, regulating the temperature. On Earth, the role of the black daisies (absorption of sunlight) is represented, among other things, by forested areas, cities with dark roofs and ocean areas rich in dark algae. The function of the white daisies (reflection of sunlight) is represented by polar ice caps and expanses of clouds.

> *"The planetary albedo is partitioned into a component due to atmospheric reflection and a component due to surface reflection by using shortwave fluxes at the surface and top of the atmosphere in conjunction with a simple radiation model. The vast majority of the observed global average planetary albedo (88%) is due to atmospheric reflection. Surface reflection makes a relatively small contribution to planetary albedo because the atmosphere attenuates the surface contribution to planetary albedo by a factor of approximately 3"*. [30]

### *3.2. The Fundamental Difference: Regulation and Anti-Regulation*

As illustrated on the left-hand side of Figure 2, in Daisyworld, an increase in the temperature of the planet is contrasted by the two balancing loops, (**B1**) and (**B2**), which, by automatically varying the masses of daisies, modify the intensity of the albedo effect to bring the temperature back to equilibrium values, rebalancing even the population of daisies itself. However, on Earth, the mechanism is reversed, as reinforcing loops are produced, (**R1**) and (**R2**), as described on the right-hand side of Figure 2. The model shows that, instead of being counteracted, the increase in temperature is amplified; loop (**R1**) is activated as heating produces a melting of the polar ice cap (and mountain glaciers), thereby reducing the albedo effect and causing a further increase in temperature. Loop **(R2)** shows how warming favors the growth of forest masses and algae, which, in turn, reduce the planet's reflective surfaces. The joint action of the two reinforcement loops produces the disastrous effect of the continuous increase in global warming, which is intensified if we consider the greenhouse effect, to which human activity contributes.

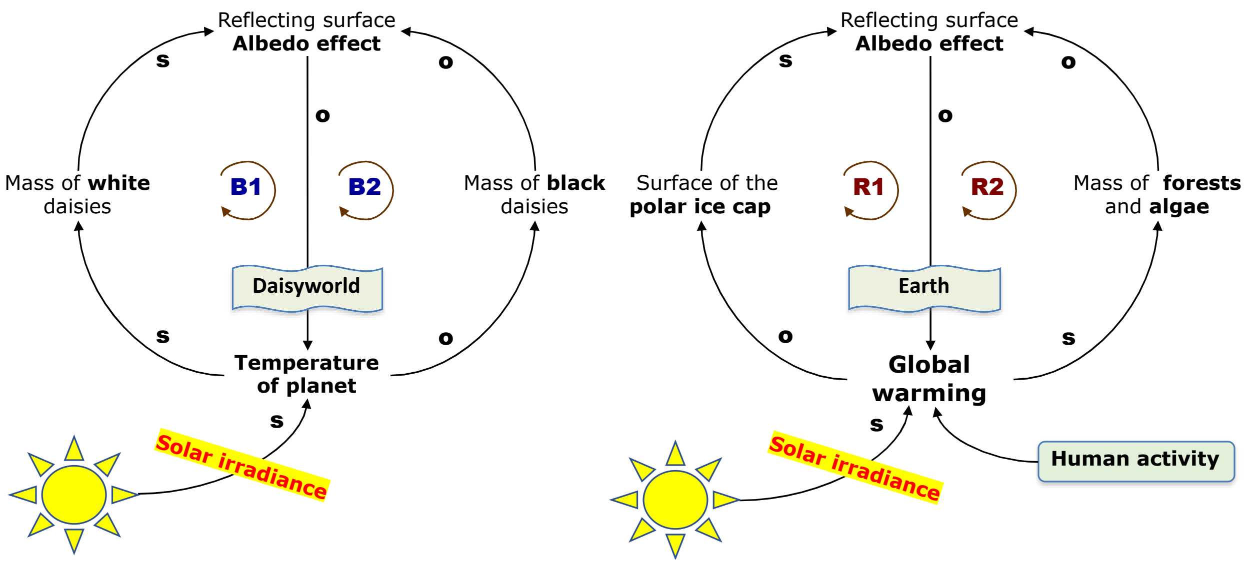


**Figure 2.** Comparison of Daisyworld and Earth.

## 4. Global Warming as the Output of a "Productive Machine": The Global Economic System, Population and the Aspiration for Well-Being, The GEAM Model

### *4.1. Greenhouse Gases and the Greenhouse Effect*

Global warming on Earth must be considered a medium-to-long term problem whose harmful effects cannot be perceived day by day, but, due to the consequences that will be produced in the coming decades, perhaps in less time than predicted. Even the younger generations, who are attentive to climate change, are aware of these consequences, for example, the unimaginable increase in sea levels, weather disturbances, the breakup of glaciers, drought, floods and other violent and increasingly frequent weather phenomena. Some argue that this damage could lead to faster-paced economic development in the form of houses to be reconstructed, entire cities transferred to new locations, new products, etc., resulting in even greater temperature rises [13].

As observed in the previous section, global warming does not depend so much on solar radiation but on the greenhouse effect from the continuous emission into the atmosphere, because of man's activities as well as natural events, of greenhouse gases such as carbon dioxide, nitrous oxides, methane, perfluorocarbons, hydrocarbons, sulfur hexafluoride and water vapor, which form a barrier to the dispersion of the heat produced by solar irradiation [31,32]. Just as in a greenhouse, heat is trapped and heats the planet's atmosphere; consequently, when the *greenhouse effect* becomes more intense, a gradual but continuous increase in the overall temperature of the Earth's atmosphere is produced (together with other phenomena)—as detected with accurate measurements—which is detrimental to survival on the planet.

*"Three major pollution issues are often put together in people's minds: global warming, ozone depletion (the ozone hole) and acid rain. Although there are links between the science of these three issues (the chemicals which deplete ozone and the particles which are involved in the formation of acid rain also contribute to global warming), they are essentially three distinct problems. Their most important common feature is their large scale"*. [33] (Preface)

*"Greenhouse gases are considered to be the most important cause of global warming in many models that explain the phenomenon"*. [23] (p. 345)

The first question we must answer is why there has been an increase in the emission of greenhouse gases and why this seems unstoppable, at least for now, even if, thanks to the continuous and widespread dissemination of information, everyone is now aware of the need to contain them. At the dawn of life on our planet, natural events, forests, oceans, animals, etc., favored the creation of the greenhouse effect, which produced and maintained a comfortable temperature for living. When the population increased, to satisfy their needs and aspirations [34], man sought to increase the productivity of his labor, thereby generating three great "transformations", i.e., the agricultural revolution, the breeding revolution and the industrial revolution [35]. As Carlo Cipolla effectively demonstrated in his seminal work, The Economic History of World Population [36], the increase in productivity implied an increase in the use of energy. During the first two revolutions, energy came predominantly from humans, from beasts of burden and from the natural wind of water currents; the production of greenhouse gases was of limited intensity.

With the industrial revolution, the increase in productivity took place thanks to machines driven by the steam engine, as well as plants and equipment, whose construction (the production of iron, steel and other metals) and operation (motorized movement) required a large and increasing amount of energy, added to which was the energy needed for the extraction of minerals. The first source of energy was from the combustion of fossil coal, which was relatively abundant, easy to find, extract, transport and use (trains and steamships powered by steam produced from self-transported coal). Subsequently, with the progress of technology, coal was gradually replaced by other fossil fuels, oil and gas, available in almost unlimited quantities by then and relatively easy to extract with new technologies; above all, they were easy to transport (oil and gas pipelines) directly into homes and factories at a contained cost. The massive use of fossil fuels has led to an acceleration in the production of greenhouse gases and, above all, of carbon dioxide, $CO_2$, the gas that today contributes the most to the greenhouse effect, both in terms of the quantities produced and its diffusion in almost every part of the world. However, the use of coal has not disappeared; many densely populated countries, rich in coal, are still reluctant to abandon its use, creating $CO_2$ flows of significant magnitude [37].

### *4.2. The Engine of Global Warming: Global Economic Activity*

Following one of the fundamental principles of systems thinking, according to which, in observing the world, it is necessary to place oneself at a sufficient height to see the trees (micro) and the forest (macro) at the same time [23] (p. 114), I propose a model, sufficiently detailed and complete, that not only can explain the relationship between greenhouse gas production and *global warming* but also indicate the guidelines of a possible *control strategy* for global warming.

In light of the above considerations, it is simple to understand which human activities cause $CO_2$ and other gases emissions. Man needs to arrange goods and services for his own existence that are produced, transported and distributed by companies—from food to furniture, furnishings, cars, holidays in distant places, etc. Almost all companies burn fossil fuels to obtain energy both for the operation of machinery and for the products themselves (steel, metal casting, glass, etc.), thereby releasing $CO_2$. In many countries, coal is used extensively for industry and heating, with copious emissions, and a huge number of non-industrial engines—in cars, trucks, trains, planes, boats, etc.—are powered by petrol or diesel, producing an incessant flow of emissions. Even the electricity needed for many machines, but also for rail transport, lighting and for the countless uses we know of, is largely produced by power plants that use fossil fuels, even if a substantial part of electricity is produced by nuclear reactors. The use of energy produced by nuclear power plants that do not generate greenhouse effects, which began in the mid-1950s, has been limited after an initial diffusion because of the problem of the disposal of radioactive waste and the risk of accidents at plants leading to environmental pollution (accidents at the Three Mile Island plants in 1979, Chernobyl in 1986 and Fukushima Daijichi in 2011). Today, about 445 nuclear power plants are active in 32 countries, including Japan, with about another 50 reactors currently being built, more or less equal to 15% of existing capacity [38,39].

With the greater availability of resources, well-being increases in all countries and poverty is combated by a growing need for products and services whose production and use favor $CO_2$ emissions. Among the most polluting products are means of road transport and cars, even if this is not evenly distributed among countries; scrolling through the list of the number of cars per 1000 inhabitants in 190 countries, published by Wikipedia [40], the following data have been extracted: "USA: 816, Canada: 685, Italy: 663, Japan: 549, Switzerland: 537, France: 482, Russia: 388, China: 210, Panama: 171, Turkey: 150, Egypt: 109, Pakistan: 16, Somalia: 7, Bangladesh: 4, Niger: 7".

Although the quantitative difference in car ownership in the various countries depends, in part, on the state of public transport, it is easy to predict that the increase in national wealth will lead countries with low numbers of cars to increase their consumption. Similar considerations apply to homes, furniture, gas or electric cookers, refrigerators and freezers; the more wealth grows, the more the demand and production of goods increases, further increasing productive activity and wealth. The use of gaseous and petroleum-derived fuels is also increasing in all places where wood and coal are still used extensively to produce domestic heat. The need for fields for cultivation also pushes many inhabitants of large equatorial forests to set fire to tree-covered areas, producing deforestation and releasing large amounts of greenhouse gases, thereby slowing the process of purification from greenhouse gases.

These developments make two aspects clear.

*First*, there is a correlation among productive activity, the spread of wealth, investments and the demand for goods and services; the growth of qualified consumption leads to more intense production; however, this impacts consumption through a typical reinforcement loop mechanism that increases the emissions of greenhouse gases.

*Second*, to describe global warming, we must not limit ourselves to considering the behavior of individual agents, consumers, companies, or public and private bodies (the trees), but, instead, we need a global vision of the entire economic system (the forest).

Taking into account all these considerations, one can construct the simple model in Figure 3, the GEAM, which I suggest to be read following the sequence below.

The GEAM assumes that the "economic engine" that produces emissions that cause global warming is represented by "Global Economic Activity", namely, the system of all production and consumption activities carried out globally by "economic agents" (individuals, organizations, companies, etc.) who produce and consume. Although they operate in different areas at the *micro* and *local* levels, they give rise to a *global*, unitary economic process. In effect, by observing, today, the production and consumption processes from a "sufficient height", it is easy to realize that, in fact,

> *"Any kind of production flow is obtained not from individual production organizations but from a widespread (global) Production Network of interconnected production modules located in different places and times. All these modules are, consciously or not, necessarily connected, interacting and cooperating in a coordinated way to combine and arrange, step by step, the factors, materials, components, manpower, machines and equipment to obtain flows of products—final goods, in particular—and to sell these where there is a demand for them"*. [35]

The Global Production Network represents a Global Economic Machine that develops the Global Economic Activity.

Since global warming is a *global* phenomenon and not a *local* one, it is necessary to observe the totality of economic activities, the macro global economic activity, and not to dwell on the micro economic activities of the different agents. In fact, it is the global economic activity that consumes fossil fuels for the global needs of production and consumption, thus producing greenhouse gas emissions—$CO_2$ in particular. The latter, together with emissions from other sources not attributable to man, contribute to the increase in the amount of greenhouse gases, causing the heat deriving from solar irradiance to be trapped in the atmosphere, resulting in an increase in global warming.

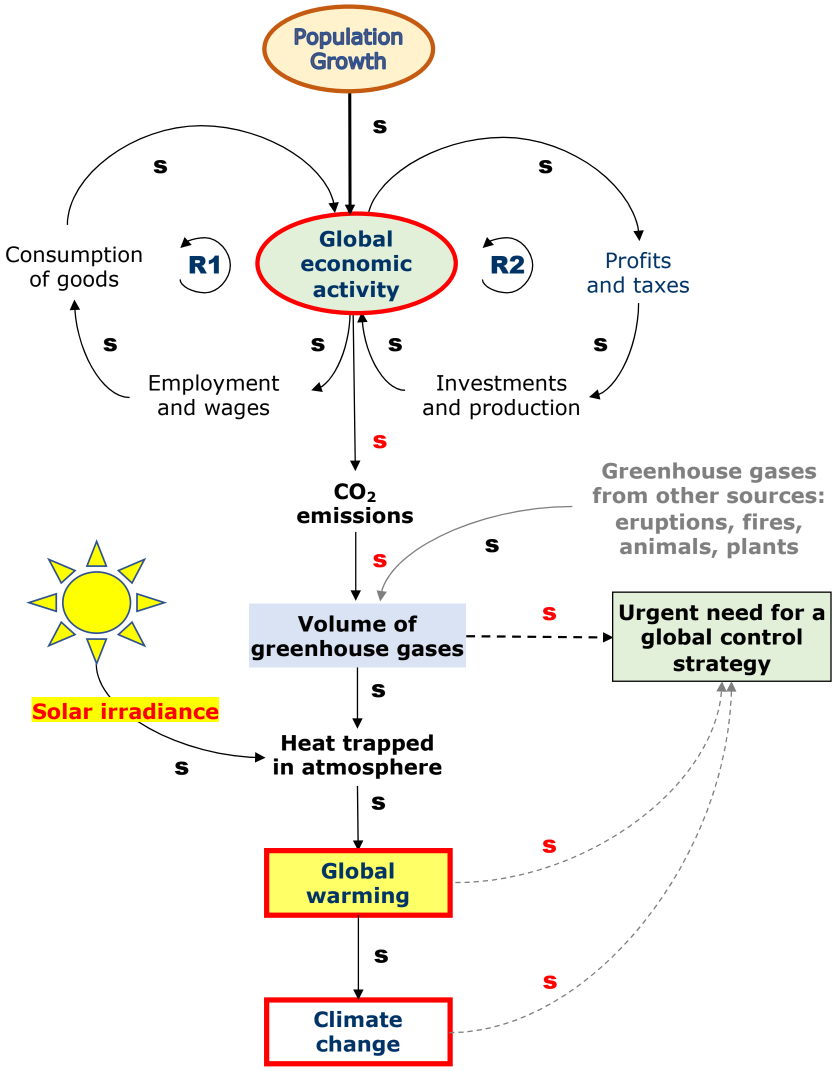


**Figure 3.** GEAM, Global Economic Activity Model, describing the system generating global warming.

Economic activity is a continuous process that is maintained and developed over time, since it produces obvious advantages, as described by the two "strengthening loops". These loops lead, in turn, to the gradual increase in global economic activity. On the one hand, the production of goods and services generates employment and wages that allow households to buy and consume the goods and services necessary for survival, thereby creating "demand" and generating loop (**R1**). On the other hand, economic activity produces profits, which are the "engine" of the investments necessary to maintain and develop the production processes. Economic activity also generates taxes for countries and other organizations that translate into resources for consumption (public workers' salaries, subsidies, etc.) and for investments in public works and public companies, in this way forming loop (**R2**). Thus, the two reinforcement loops generate a constant increase in global economic activity, which, in turn, reinforces the other variables in the loops, all of which leads to an increase in $CO_2$ emissions, the greenhouse effect and, ultimately, global warming.

A fundamental role in this process is played by world population, a variable that has not yet been explicitly considered but which is fundamental in understanding the dynamics of global warming. In fact, global economic activity is not an abstract process but takes place only because it requires a population that needs goods to consume, provides work and creates demand, thereby encouraging entrepreneurs to risk the investments necessary for production in the "hope" of a return on risk capital.

The GEAM operates even when the size of the world population is *constant* over time; economic activity increases as the so-called "poor" segment of the population requires *work* and *goods* to move to the "well-off" segment of the population and it increases even more as the latter moves into the so-called "rich" segment of the population (in 1999, 3775 Ferrari cars were produced and sold; in 2009, 6250; in 2019, 10,131 [41]). Clearly, the increase in living standards is caused by, but also presupposes, an intensification of global economic activity; therefore, between these two variables, there is a reinforcement loop—which is implicit in the model, although not formally expressed—which also operates under the hypothesis of a stable world population.

As is well known, in recent millennia, the world population has been constantly expanding, with wealth becoming more and more widespread. The population on Earth has grown from around 300 million, 2000 years ago, to 7.5 billion, today, representing a very low average growth rate—CAGR = 0.0016. The population, in 1800, was around 980 million and, today, it stands at 7.5 billion, which means that, over the last 200 years, the average growth rate has risen to CAGR = 0.0121. Man's ideational capacity has enabled him to increase his *productivity* in all sectors, so that the Malthusian limits [42] to population growth are continually expanding. If this trend continues, the United Nations predicts that, by the end of the century, about 11 billion people will populate the Earth, with a growth in CAGR compared to today equal to 0.0341. However, some demographic studies claim that, in the near future, the population of the globe will begin to decrease, even in the absence of conflicts and cataclysms, because of the following four fundamental, interacting factors: (1) the reduction in the birth rate; (2) the progressive ageing of the population due to improved living conditions and progress in medicine, with a consequent reduction in "fertility"; (3) urbanization, which increases stress and reduces leisure time and the desire to have children; (4) the cultural change toward women working, which, by tending to increasingly consolidate the working position of women, leads them to viewing a large family as presenting objective difficulties [43,44].

In conclusion, the growth in the population on Earth, as well as the natural tendency of man to seek better living conditions, supports loop (**R1**) and "forces" an expansion in global economic activity, thus intensifying greenhouse gas emissions and, consequently, the growth in global warming. In GEAM, population dynamics is considered as an *exogenous* variable; in the model in Figure 3, it is represented as an input to global economic activity that bolsters global warming.

## 5. The Three-Lever Strategy for the (Difficult) "Artificial" Human Control of Global Warming: The Removal–Consumption–Production Strategy

### 5.1. The "Social Alarm"

As observed, the greenhouse effect has developed since the early stages of our planet's existence, allowing solar radiation to produce a favorable climate for life on Earth. With the advent of man, natural conditions, together with the modest action of embryonic global economic activity, led to a growth in global warming that was modest at first but subsequently became more sustained. For centuries, man was not aware of this phenomenon due both to its modest intensity and the lack of instruments for observing and measuring it. The scientific awareness of the greenhouse effect is attributable to studies by Joseph Fourier, who, in 1824 [45], discovered that the energy irradiated on Earth by solar radiation was greater than that irradiated from the Earth into space, thereby producing a progressive warming of the planet [46]. A few years later, Eunice Newton Foote, in his work titled "Circumstances Affecting the Heat of the Sun's Rays" (1856) and as a result of his experiments, concluded that carbon dioxide affected the temperature of the atmosphere more than other gases did [47].

> *"An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature... must have necessarily resulted"*. [48]

With the right technologies, adequate statistical methods and a capillary system of measurement, man became aware of the dangers from an increase in global warming attributable to greenhouse gases. The population was informed of this risk and awareness was raised especially among young people in schools, causing fear of the spread of the increase in warming, thereby igniting a real "social alarm" that was reinforced by the disastrous events around the world attributed to global warming [49].

The social alarm prompted countries to establish supernational regulators that would set rules for the control of greenhouse gas emissions, with a special focus on $CO_2$, whose principal source are the emissions from global economic activity. Several measures—or *macro-levers* of control—have been theorized, which, taken jointly by all governments, would constitute a true *control strategy.* To illustrate this, the model in Figure 3 was adapted as shown in Figure 4. To highlight the components of this *strategy*, it is useful to group the multiple specific levers that can be implemented by the different governments into only three *macro-levers* of control, indicated in the box on the left-hand side of the model in Figure 4. The cause-and-effect dynamics of the integrated model in Figure 4 are indicated below.

When populations, through information disseminated from multiple sources, become aware of global warming and its effects, which are beginning to manifest themselves and become worrisome, a social alarm arises (shaded box) ("**s**") which intensifies ("**s**")—conferences, debates in the media, demonstrations, student movements, etc.—thereby producing a social and political movement that results in tolerance limits on the emission of greenhouse gases ("**s**") by countries being imposed by supranational authorities. Consequently, it becomes increasingly urgent ("**s**") to develop a control strategy ("**s**") by means of international treaties, such as the Kyoto protocol, which was signed as part of the United Nations Framework Convention on Climate Change (UNFCCC) by over 160 nations on 11 December 1997, during the COP3 convention in Kyoto. Other international agreements followed, such as the Paris Agreement limiting warming to 2 °C and by "pursuing efforts" to keep it below 1.5 °C. An in-depth analysis of the objectives of the Paris agreement, which poses "*the legal precautionary principle, that this objective indicates a legal imperative towards zero emissions globally within a short timeframe*", is in [50].

In the COP20 meeting held in Rome in October 2021 and the COP26 meeting that followed in Glasgow in November 2021, a ceiling was set for new emissions. However, the containment of emissions had already been indicated as the first objective at the COP 26 meeting, held in Glasgow in November 2021 [51] (https://ukcop26.org/cop26-goals/) (accessed on 29 November 2021).

1. Securing global net zero by mid-century and keeping 1.5 degrees within reach.

Countries are being asked to come forward with ambitious 2030 emissions reductions targets that align with reaching net zero by the middle of the century.

To deliver on these stretching targets, countries will need to perform the following:

- Accelerating the phase-out of coal;
- Curtailing deforestation;
- Speeding up the switch to electric vehicles;
- Encouraging investment in renewables.

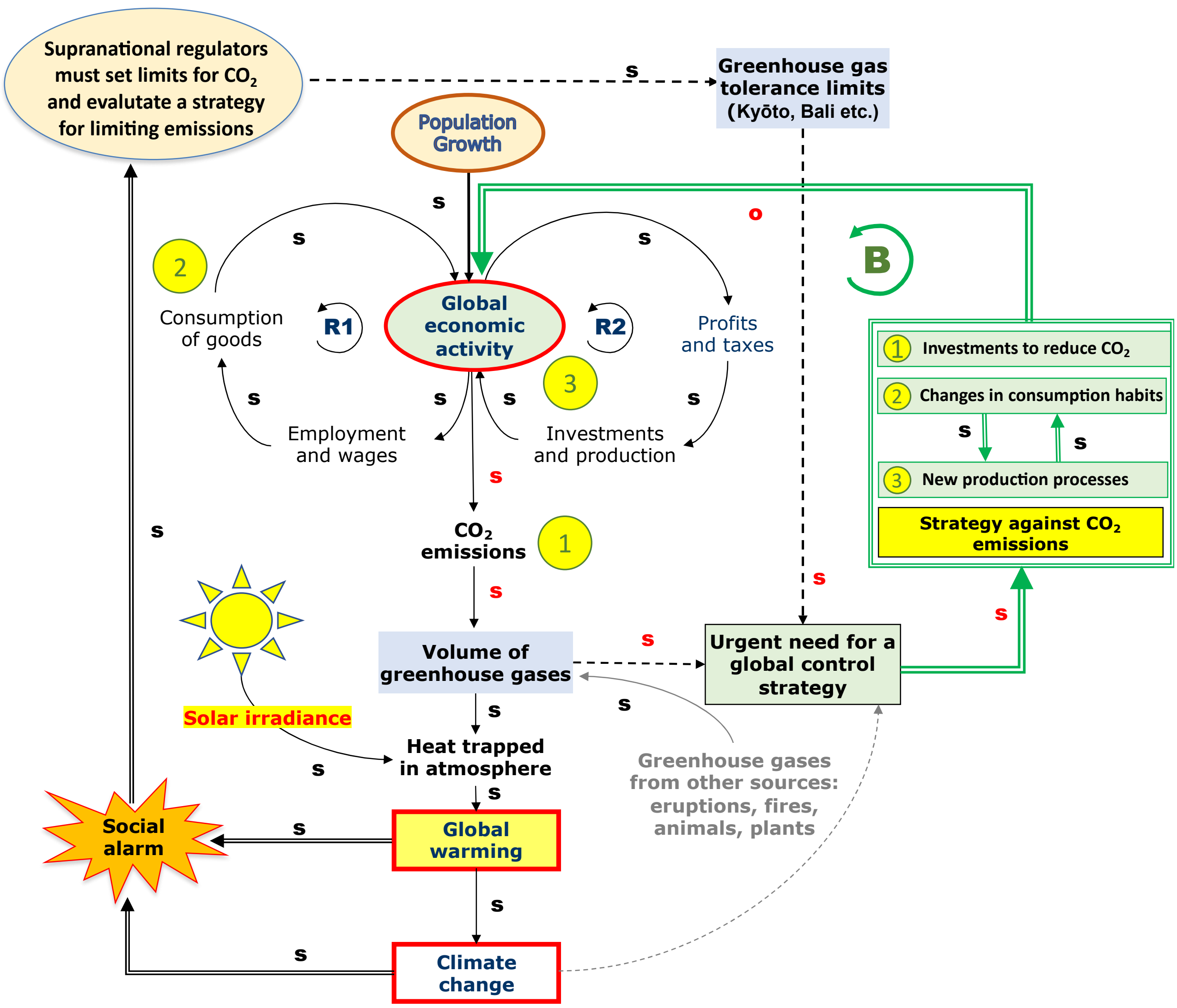


**Figure 4.** Social alarm and the removal–consumption–production strategy.

These treaties oblige industrialized countries, which are responsible for the largest emissions of polluting substances, to develop a concrete strategy of actions to reduce their emissions by a minimum of 5.2% from 2008–2012 with respect to 1990, the base year of reference for emissions. More recently, a dramatic reduction in greenhouse gases (25–40% by 2020) was decided in 2007 with the Bali agreement. The Heads of Government also acknowledged that efforts are planned to improve the financial help offered from richer countries to poorer ones and that multilateralism, i.e., the coordinated actions of all countries, is fundamental for the control of global warming.

### 5.2. The "Removal–Consumption–Production Strategy" to Control Global Warming

The model in Figure 4 briefly highlights a strategy with three macro-levers (indicated in the right side of the box) to reduce the divergence between actual $CO_2$ levels and those the regulators have imposed. The model cannot present all the actions produced by each macro-lever, as these are too great in number.

The global strategy activates above all the operational levers (Box 1, in Figure 4) which consist in financing measures for investments to reduce $CO_2$ emissions as much as possible below the tolerance limits established in the agreements. However, the social alarm moves governments to undertake a cultural change to modify consumption habits (Box 2, in Figure 4), in an attempt to limit the consumption of goods whose production, transportation and consumption produce a large amount of greenhouse gases. At the same time, governments must take measures to modify the production processes (Box 3, in Figure 4), again with the aim of reducing emissions of $CO_2$ and other greenhouse gases. Levers 2 and 3 are independent but mutually reinforcing.

The implementation of this macro-strategy produces the overall effect of reducing emissions because the *balancing* loop (**B**) is activated according to the below closed causal chain (loop (**B**) can also be understood by starting from other variables).

[*Start* of Loop (**B**)]

[1] + global warming → + Climate Change ?→ + social alarm [*same* direction of variation, "**s**"]
[2] + social alarm → + measures by the supernational regulators [*same* direction, "**s**"]
[3] + measures by the supernational regulators → + limits to Greenhouse gas emissions [*same*, "**s**"]
[4] + tolerance limits to greenhouse gas emissions → + urgency of a strategy of control ["**s**"]
[5] + urgency of a strategy of control → + activation of the strategy against emissions ["**s**"]
[6] + activation of the strategy → - negative effects of global economic activity [*opposite* direction, "**o**"]
[7] - effects of global warming on economic activity?→ - $CO_2$ emissions ["**s**"]
[8] - $CO_2$ emissions → - increase in the amount of greenhouse gases ["**s**"]
[9] - increase in the amount of greenhouse gases?→ - heat trapped in atmosphere ["**s**"]
[10] - heat trapped in atmosphere → - global warming (+ slowdown in growth ["**s**"])

[*End* of Loop (**B**)]
[Go to *Start* to begin a second cycle]

If successful, loop (**B**) reduces the level of global warming or, at least, slows its increase. If the emission limits set by the supernational regulators are not yet reached, loop (**B**) would have to repeat its cycle, even several times, if necessary, over the years until the limits are attained in subsequent approximations. Since it has a *balancing* effect, loop (**B**) contains, within it, the danger that the governments will "let their guard down" when the results appear to have been achieved. Not "letting their guard down" means that the governments, once they have obtained a level of global warming that is not harmful, must not relax the intensity of their strategic action but intensify it; in fact, if global warming stabilizes or decreases, the social alarm could also subside, with the risk that the control strategy is loosened, leading to a new growth in global warming. The result would be a renewed need to intensify control so that a cyclical effect does not occur. It is easy to perceive this danger by retracing the previous steps in loop (**B**)**,** beginning by rewriting the first causal chain as below.

[*Start* of Loop (**B**)]

[1] global warming →—social alarm [same direction of variation, "s"]

[continue]

It is important to note that the three strategic areas indicated in Figure 4 are not mutually exclusive but *complementary*; most of the specific interventions that governments can take in each of them require related interventions in the other two areas.

### *5.3. Some Examples of the Strategic Levers to Control Global Warming (a Brief Discussion)*

Although it is not possible for me to go into detail given the theoretical nature of this paper, it is useful to highlight how, in the context of *strategic area* 1—investments to reduce $CO_2$—the fundamental action is to finance measures to reduce the use of fossil fuels, coal, oil and natural gas. This would trigger a "decarbonization" process in the global energy system [52] to replace the energy obtained from polluting fuels with "clean", non-polluting energy, in particular with electricity obtained from "renewable sources" [53], using *photovoltaic panels,* which directly convert solar energy into electricity; *solar cells*, whose heat can be used to produce steam for electric turbines; *wind turbines* on land and sea; *tidal energy devices,* which convert the energy of waves and tides; technology for the use of geothermal energy from the Earth—geysers and boraciferous shower heads—allowing man to use terrestrial heat; and the use of methane and hydrogen as well as nuclear power plants.

> *"In the long run, we need to be aware that renewable energies may have limitations. The European Commission tells us that they may not be enough to achieve the ambitious targets we have set ourselves for 2030 and 2050. Therefore, we need to start developing viable alternatives now, because it will only be possible to fully enjoy them in a few years' time. In the meantime, we need to invest in innovative carbon capture technologies"*. (Mario Draghi, COP26. https://www.governo.it/it/node/18445) (accessed on 7 January 2022)

The elimination of or reduction in fossil fuels is a control lever that also affects *strategic area* 3—new production processes—because interventions will have to be envisaged to encourage the investments industries will have to make to replace machinery or engines powered by fossil fuels; new plants will have to be produced, new equipment devised, and new products designed and proposed. In many countries, an effort is underway to encourage the consumer to replace traditional cars with electric ones. This change in the structure of the means of transport must be accompanied by the creation of a network of charging stations on motorways and cities, as well as the spread of wall boxes and domestic and private systems for the fast charging of car batteries. The replacement of traditional motor cars with electric cars is not only a production problem but one that concerns *strategic area* 2—changes in consumption habits—because owners and drivers will have to get used to the new performance, costs and long charging times. In conclusion, these interventions, designed to reduce greenhouse gases, will change the size of the necessary investments, the production systems that will have to reconvert their processes and products and the transportation habits of individuals [54].

Another example regarding the individual interventions concerning changes in eating habits will make it easier to understand the interactions between the three strategic areas. A non-negligible amount of greenhouse gases is produced by cattle during their digestive cycle through the emission of worrying amounts of methane that remain in the atmosphere for about 10 years. Intensive cattle and pig farming is also a source of large amounts of greenhouse gases (carbon dioxide, methane and nitrous oxide) not only from the digestion process but also from the decomposition of manure. To eliminate these emissions, people's *eating habits* must be changed by convincing them to reduce beef consumption in favor of non-polluting alternatives by following a vegetarian and vegan diet, one based on non-beef alternatives for meat, one based on fish and seaweed, even one that includes insects and the consumption of *zero-kilometer* products. However, all this would require huge investments to convert livestock farms, compensate farmers and change the supply of food in hypermarkets. Processes must be introduced to grow algae [55] and to enhance the breeding of alternative animals and insects safely and in large quantities [56,57], converting these sources into food accepted by consumers. Restaurant menus will also have to be converted, but, first and foremost, individuals must be convinced to change their diet. The change in eating habits (strategic lever n.1), towards foods not deriving from animal species that produce and emit methane as a by-product of their digestive cycle, also involves a modification of farming processes that also impact land use (strategic lever n. 3). The strategic aspects for achieving these changes are detailed in [15].

Finally, in strategic area 1, some attempts are being studied and implemented to artificially absorb the gas from the atmosphere by means of "carbon capture" devices [58,59].

> *"It is physically possible to capture $CO_2$ directly from the air and immobilize it in geological structures. Air capture differs from conventional mitigation in three key aspects. First, it removes emissions from any part of the economy with equal ease or difficulty, so its cost provides an absolute cap on the cost of mitigation. Second, it permits reduction in concentrations faster than the natural carbon cycle: the effects of irreversibility are thus partly alleviated. Third, because it is weakly coupled to existing*

*energy infrastructure, air capture may offer stronger economies of scale and smaller adjustment costs than the more conventional mitigation technologies"*. [59]

Finally, some attempts have been made to artificially absorb gas from the atmosphere, such as the creation of air filtering units that can extract $CO_2$, transforming it into coal and diamonds [60]; or the production of $CO_2$-absorbing *panels* that cover the facades of skyscrapers. Other artificial levers have been designed, but not all of which, even though apparently rational, are effective.

Another non-traditional lever, apparently simple to implement and requiring relatively limited investment and means, aims at increasing the albedo effect by employing a fleet of aircraft to spray large volumes of seawater on large ocean surfaces [61]; since it contains microscopic salt particles, the seawater spray favors the formation of large layers of white clouds that are intended to create a barrier to radiation by reflecting a great amount of solar radiation to produce the desired albedo effect, thereby limiting warming [62–66]. However, this lever was suspended due to its harmful side effects; the white clouds, when directed towards the mainland, caused intense rains.

*"The idea behind the marine cloud-brightening (MCB) geoengineering technique is that seeding marine stratocumulus clouds with copious quantities of roughly monodisperse sub-micrometre sea water particles might significantly enhance the cloud droplet number concentration, and thereby the cloud albedo and possibly longevity. This would produce a cooling, which general circulation model (GCM) computations suggest could—subject to satisfactory resolution of technical and scientific problems identified herein—have the capacity to balance global warming up to the carbon dioxide-doubling point"*. [67] (p. 4217)

## 6. The Gulf Stream: A "Natural" Lever for the Self-Control of Global Warming through Glaciation

### *6.1. The Mitigating Effect of the North Atlantic Climate and the Consequences of a Possible Slowdown of the Gulf Stream*

Several academics [68,69] hold that, alongside the "artificial" control levers implemented by man, there is also a *natural control lever* that can go beyond, or at least support, the strategy of the three macro artificial levers shown in Figure 4. This lever acts as an autonomous *natural* control system that *automatically* modifies the structure of the natural environment that produces global warming. This natural automatic *lever* is the cooling of the Gulf Stream due to global warming itself, which, by warming the planet, produces a massive melting of the ice cap that pours a huge volume of fresh cold water, which is also poor in salt, into the North Atlantic Ocean, thereby cooling the ocean currents.

*"The Gulf Stream carries the warm, poleward return flow of the wind-driven North Atlantic subtropical gyre and the Atlantic Meridional Overturning Circulation. This northward flow drives a significant meridional heat transport. Various lines of evidence suggest that Gulf Stream heat transport profoundly influences the climate of the entire Northern Hemisphere and, thus, Europe's climate on timescales of decades and longer"*. [70] (p. 113)

The Gulf Stream is, above all, a natural carrier of heat to areas of northern Europe. Seawater, thanks to favorable natural conditions, warms up in the Gulf of Mexico and becomes less dense and light. Archimedes' law pushes heated water in the South towards the cold water of the North, forming a "warm" current that travels to the surface; the Coriolis effect, which is a result of the Earth's rotation [71], directs this current from the *southwest* to the *northeast,* that is, from the Gulf of Mexico to the areas of northern Europe, skirting England and areas even further north, as shown in Figure 5.

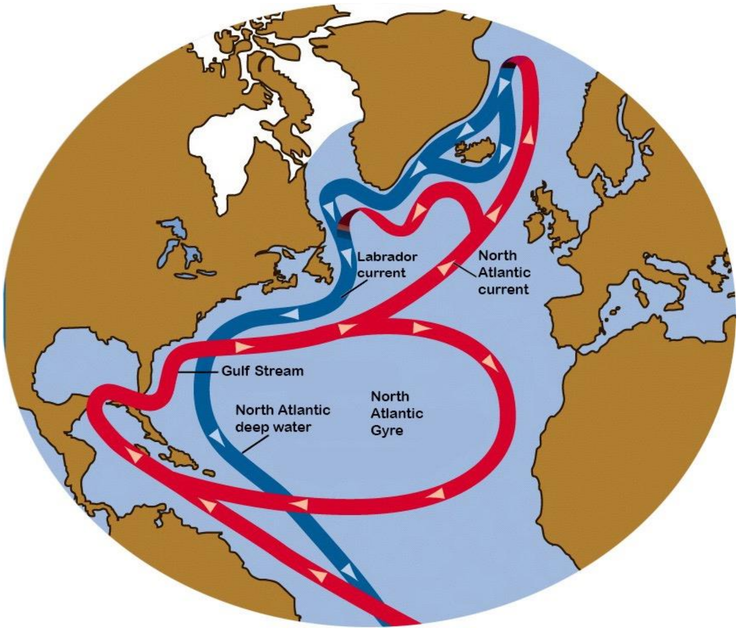


**Figure 5.** Circulation of the North Atlantic Gulf Stream (source, [72]).

The path of the Gulf Stream to the north ends when it meets the cold polar waters, which slow it down, producing the beneficial heat that creates the mild northern temperatures. The cooling waters reduce salinity and "sink" toward the bottom of the ocean, returning to the Gulf of Mexico where a new cycle of warming and northeast flow begins. The Gulf Stream is not a one-way flow but a "circuit" that flows incessantly, year after year. The higher the mass of cold water that the current encounters, the more it loses its speed and is pushed toward the ocean floor, ending its ascending cycle. Because of the expected interruption in the path of the Gulf Stream, a smaller mass of warm water would flow into the North Atlantic reducing the heat supply of the northern waters, which would become even colder (reinforcing loop) with the risk of a new glaciation throughout northern Europe, even as far as the Alps. This hypothesis is supported by a large number of data [73] and even the study of past weather phenomena appears to show that the last relevant ice age, some 8500 years ago, was in fact caused by a phenomenon such as the one just described [74].

Despite the serious damage to the flora, fauna and inhabitants of the affected areas, the glaciation of northern Europe would, technically speaking, produce a beneficial effect on the control of global warming by increasing the albedo effect and restoring the conditions for the two-lever control mechanism to occur, similar to what we witnessed in Daisyworld; on the one hand, the extension of the ice mass in northern Europe (which corresponds to the increase in the mass of white daisies) and, on the other, the reduction in the green expanse of northern forests (corresponding to the reduction in the mass of black daisies) represent the joint effects that can control global warming for a sufficiently long period.

### *6.2. The Gulf Stream as a Natural Control Lever for Global Warming*

The description above is summarized in Figure 6. Loop (**B**) illustrates how the cooling effect triggered by global warming itself has the potential to mitigate the effect of global warming. Loop (**R**) illustrates that the glaciation produced by the cooling of the Gulf Stream would lower the temperatures in northern Europe through the two levers that extend the polar ice caps and cover the forest/green zone with ice, thereby producing the albedo effect that would reduce the temperatures in the northern regions and, as a result, global warming. The causal loop diagram defines, in fact, a "natural control system" (if it should ever spontaneously self-activate) capable of dealing with the global warming problem.

The bottom image in Figure 6 represents the effects of the causal control loop indicated at the top. The longest red line in the Atlantic Ocean indicates the ascending and warm Gulf Stream; the blue line indicates the descending cold current which has given up its heat; the shorter red and blue lines depict the Gulf Stream that would have sunk early due to the low temperatures of the northern waters, which would have cooled due to the pouring of large volumes of the melted Arctic ice sheet into the ocean; the large blue arrows represent the advance of ice in the northern regions, which would gradually cover the belt of forests the area had been once rich in. Therefore, glaciation would produce an enhancement of the albedo effect similar to what occurs in the two-lever control simulated in Daisyworld.

The question marks superimposed on the areas in the Southern Hemisphere indicate that we cannot predict the effects produced there by the slowdown of the Gulf Stream. Since ocean currents are connected to each other in a lattice network of streams, the warm water generated in the Gulf of Mexico forms a flow directed not only to the north but also to the south (dotted red line). Therefore, it is plausible to imagine that the cooling of a considerable part of the Atlantic Ocean would also affect the temperature of the waters of the other oceans by altering the displacement of heat from the lattice network of the other ocean currents.

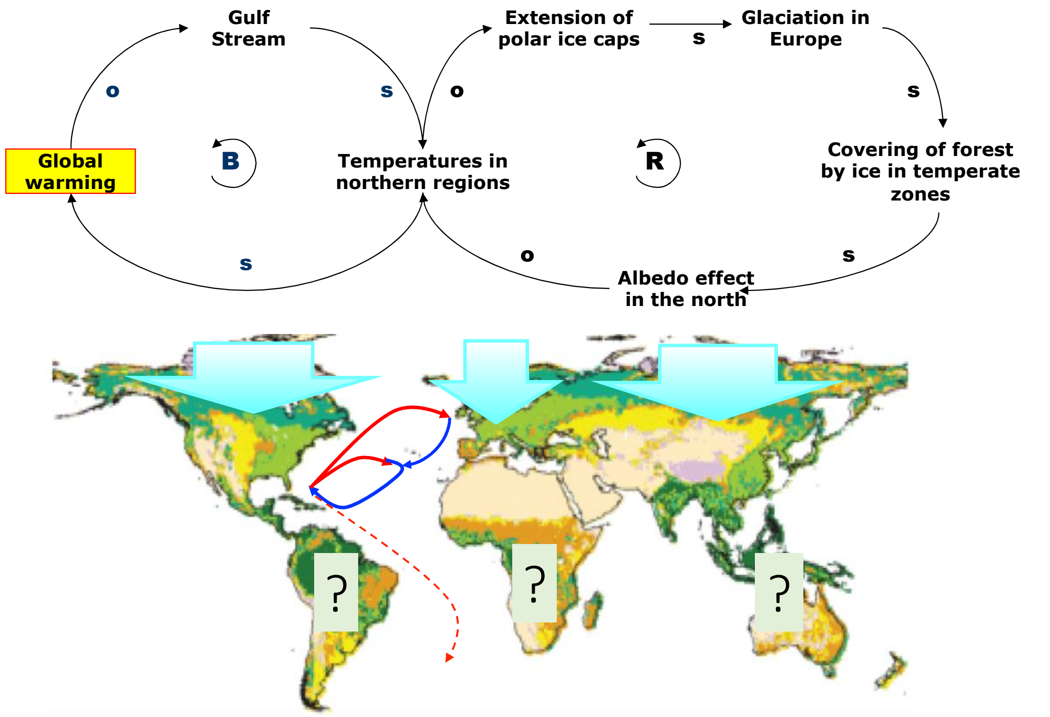


**Figure 6.** How the Daisyworld effect can control global warming.

A *cooling effect* can also be produced from the explosions of the "great volcanoes", which eject a large volume of ash into the atmosphere, preventing radiation from the sun for a long period, until the released particles are deposited on the ground. Over the millennia, there have been numerous large volcanic explosions [75–77], with devastating, if temporary, effects [78], a relatively recent example of which is the Mount Tambora volcano, which, in April 1815, produced the largest volcanic explosion in recent history, causing the event known as "The Year Without a Summer". The explosion, in fact, ejected large volumes of ash and aerosols into the air and the smallest particles spread through the Earth's atmosphere causing a "barrier effect" to solar radiation that resulted in a cooling of the planet by 3 degrees Celsius. This effect lasted a long time, until the particles gradually fell to the ground. The considerable fall in temperature interrupted the summer, preventing crops from ripening and causing a considerable famine. For this reason, 1816 is remembered, in the north, as "The Year Without a Summer" [79–81].

## 7. Four Dangerous "Natural" Loops That Block the Human Control of Global Warming

In contrast to the potential positive effect from the slowdown of the Gulf Stream because of global warming (Figure 6), there are, unfortunately, other "natural" phenomena—produced, or accentuated by global warming itself—that favor, rather than counteract, the increase in warming, thereby producing dangerous *reinforcing loops* that can act simultaneously and cumulatively for a long time. Some phenomena are already mentioned in part in Section 6, but it is appropriate to highlight four of them, the joint action of which is represented in Figure 7.

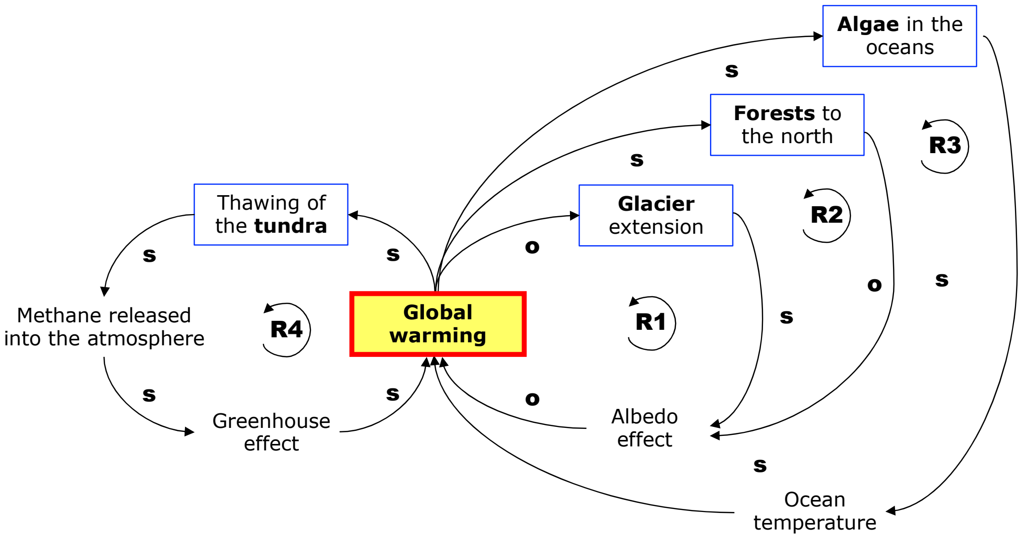


**Figure 7.** Action of four harmful reinforcing loops that increase global warming.

### *7.1. Decrease in the Albedo Effect Due to the Shrinkage in Reflective Surfaces*

The first natural phenomenon is represented by the increasingly faster melting of the polar ice and the mountain glaciers above 3000 m caused by the increase in global warming. As a result, the icy areas shrink and, since they reflect less solar radiation, the albedo effect is reduced and the contrast to solar radiation limited, thereby causing a further reinforcement of global warming as indicated in loop (**R1**) in Figure 7 [82].

> *"Polar ice caps are melting as global warming causes climate change. We lose Arctic Sea ice at a rate of almost 13% per decade, and over the past 30 years, the oldest and thickest ice in the Arctic has declined by a stunning 95%. If emissions continue to rise unchecked, the Arctic could be ice-free in the summer by 2040. But what happens in the Arctic does not stay in the Arctic. Sea ice loss has far-reaching effects around the world".* [83]

> *"Arctic experts say, the accelerated melting could produce an ice-free summer Arctic by 2030. The environmental repercussions from such an extensive defrosting of the region are enormous. Open, dark water absorbs heat from sunlight, while an icy skin reflects much of it back into space. Hence, the more open ocean, the faster the melting of the remaining ice, creating a feedback loop that could eat away at the adjacent Greenland Ice Sheet".* [84] (online)

Resistance to this phenomenon is not possible at the planetary level, although at the local level, in mountain areas, "palliative interventions" have been attempted, such as covering the glaciers with vast "geotextile" white sheets to reflect the sun's rays to prevent the heat from melting the ice for a period (Figure 8).

**Figure 8.** The covering of the Presena glacier in northern Italy (sources, [85,86]).

### *7.2. Reduction in the Albedo Effect Due to an Increase in Forest-Covered Areas*

In parallel with the preceding effect, global warming, despite manmade deforestation, favors the expansion of forests into increasingly larger areas previously covered in ice, since mild temperatures favor plant growth. The dark leaves of forest trees not only trap heat, producing aerosols that interact with methane [87,88], but, in the long run, also aid in reducing the albedo effect by creating a strengthening loop, (**R2**) in Figure 7, that weakens the albedo effect, causing a further increase in global warming [89,90].

> *"Many scientists applaud the push for expanding forests, but some urge caution. They argue that forests have many more-complex and uncertain climate impacts than policy-makers, environmentalists and even some scientists acknowledge. Although trees cool the globe by taking up carbon through photosynthesis, they also emit a complex potpourri of chemicals, some of which warm the planet. The dark leaves of trees can also raise temperatures by absorbing sunlight. Several analyses in the past few years suggest that these warming effects from forests could partially or fully offset their cooling ability. . . . At the same time, some researchers worry about publishing results challenging the idea that forests cool the planet. One scientist even received death threats after writing a commentary that argued against planting trees to prevent climate change".* [91]

### *7.3. Expansion of Dark Algae*

It is well known that much of the heat from global warming is absorbed by the warming oceans; in fact, global warming is due to ocean warming. The phenomenon in (2), which affects uncovered land areas, has its counterpart in the spreading of "dark algae" in the Antarctic and in the oceans, whose temperatures rise due to global warming [92]. The masses of "dark algae", which do not reflect sunlight, further increase global warming, activating loop (**R3**), as shown in Figure 7.

> *"Harmful algae usually bloom during the warm summer season or when water temperatures are warmer than usual. Warmer water due to climate change might favor harmful algae in a number of ways: . . . Algal blooms absorb sunlight, making water even warmer and promoting more blooms".* [93]

> *"Warming in the Antarctic Peninsula has already exceeded 1.5 °C. over pre-industrial temperatures, and current Intergovernmental Panel on Climate Change (IPCC) projections indicate further global increases. Set against a background of natural decadal temperature variability, climatic changes on the Peninsula are already influencing its vegetation. With the available area for plant colonisation on the Peninsula likely to increase by up to threefold due to this warming, understanding how snow algae fit into Antarctica's biosphere and their probable response to warming is critical to understanding the overall impact of climate change on Antarctica's vegetation. . . . Several studies have used satellite observations to investigate snow and ice algae on larger scales, implicating algal blooms as significant drivers for darkening and enhancing melt of the Greenland ice sheet".* [94]

However, it should be remembered that the growth of macro algae, such as sargassum (*Sargassum*), requires the consumption of large volumes of $CO_2$, which are then "stored" in their biomass; fortunately, this causes a reduction in the greenhouse effect, counteracting global warming [95].

### 7.4. Thawing of the Tundra

Together with the phenomenon in (1), global warming thaws the immense tundra (loop (**R4**)) [96–98], whose frozen soils unfortunately trap methane bubbles; this melting releases large amounts of these methane bubbles, which increases the greenhouse effect with an intensity about 30 times greater than that produced by $CO_2$ [99–101].

> *"Because the world is getting warmer, permanently frozen ground around the arctic, known as permafrost, is thawing. When permafrost thaws, the ground collapses and sinks. Often a wetland forms within the collapsed area. Conversion of permanently frozen landscapes to wetlands changes the exchange of greenhouse gases between the land and atmosphere, which impacts global temperatures. Wetlands release methane into the atmosphere. Methane is a potent greenhouse gas. The ability of methane to warm the Earth is 32 times stronger than that of carbon dioxide over a period of 100 years"*. [102]

> *"Alexander Sokolov and Dorothee Ehrich spotted 15 patches of trembling or bubbling grass-covered ground. When punctured they emitted methane and carbon dioxide, according to measurements, although so far no details have been given. The reason is as yet unclear, but one possible explanation of the phenomenon is abnormal heat that caused permafrost to thaw, releasing gases. Alexander Sokolov said that this summer is unusually hot on the Arctic island, a sign of which is polar bears moving from the frozen sea to the island. Scientists have warned at the potential catastrophic impact of global warming leading to the release into the atmosphere of harmful gases hitherto frozen in the ground or under the sea. A possibility is that the trembling tundra on Bely Island is this process in action"*. [103]

> *"The impact on the climate may mean an influx of permafrost-derived methane into the atmosphere in the mid-21st century, which is not currently accounted for in climate projections. The Arctic landscape stores one of the largest natural reservoirs of organic carbon in the world in its frozen soils. But once thawed, soil microbes in the permafrost can turn that carbon into the greenhouse gases carbon dioxide and methane, which then enter into the atmosphere and contribute to climate warming"*. [104]

See Figure 9 to understand the size of the phenomenon and to estimate the huge volume of greenhouse gases that would pour into the atmosphere if trapped methane were released. The methane bubbles are also present in many lakes, a well-known example of which is Lake Abraham, an artificial lake in Canada, in Northern Saskatchewan, which has become a tourist destination because of the "performance" of its methane bubbles in the frozen water.

According to surveys conducted by the World Meteorological Organization, a U.N. agency, the economic slowdown caused by COVID-19 and the resulting lockdowns has had no visible impact on the atmospheric levels of greenhouse gases and their growth rates [107,108]. It is likely that the slowdown in emissions has begun to be counterbalanced by the effects of the four phenomena outlined above, which indicates that the prospects for humanity are not encouraging. However, it is to be hoped that these reinforcement loops will accelerate the intervention of a control strategy by man and the activation of the balancing loop provided by the Gulf Stream.

> *"Very reliable measurements allow us to track carbon as carbon dioxide ($CO_2$) in the global atmosphere but plants, soils and permafrost together contain at least five times more carbon and the global ocean at least fifty times more carbon than the atmosphere"*. [109]

**Figure 9.** Methane bubbles under Lake Abraham (1st photo) and in the frozen waters of the Tundra (sources, [104–106]).

## 8. Conclusions and Suggestions

### *8.1. The Role of Models for the Understanding of Phenomena*

> *" . . . "understanding the world" (comprehending) means in fact being able to construct coherent and meaningful mental and formal models—that make up our "knowledge"—which allow us to form and transmit new knowledge".* [110] (p. 2)

A model can be defined as coherent and meaningful if it is linked to other knowledge or models related to what we think about the world and leave us satisfied (without doubts or any questions), at most arousing further curiosity and a desire for knowledge. The most coherent and meaningful models are the systemic ones, in particular those based on the language of systems thinking. The systemic vision derives every variable (phenomenon, action and data) from processes carried out by systems with a structure of relationships among (often unknown) variables (see Appendix A). The first models we build to understand "the world" are the "mental" models, which guide our judgments, decisions and behavior.

> *"The mental image of the world around us that we carry in our heads is a model. One does not have a city or a government, or a country in his head. He has only selected concepts and relationships, which he uses to represent the real system".* [111] (p. 213)

In his book titled "Mental Models: Towards a Cognitive Science of Language, Inference and Consciousness" (1983), the psychologist Philip Johnson-Laird highlighted the cognitive function performed by mental models in the representation and understanding of the world.

> *"The psychological core of understanding, I shall assume, consists of having a "working model" of the phenomenon in your mind. If you understand inflation, a mathematical proof, the way a computer works, DNA, divorce, then you have a mental representation that serves as a model of an entity in much the same way as, say, a clock functions as a model of the earth's rotation . . . Many of the models in people's minds are little more than high-grade simulations, but they are none the less useful provided that the picture is accurate".* [112] (p. 2)

Mental models are part of the personal sphere and are subject to continuous changes; their existence can be formalized through a "language" that leads to their translation into "formal models". Mental models influence our *judgments*, *decisions and actions*, in that

> *"Our 'mental models' determine not only how we make sense of the world, but how we take action. Mental models can be simple generalizations such as 'people are untrustworthy' or they can be complex theories, such as my assumptions about why members of my family interact as they do. But what is important to grasp is that mental models are active—they shape how we act. If we believe people are untrustworthy, we act differently than if we believed they were trustworthy [ . . . ] Why are mental models so powerful in*

> *affecting what we do? In part, because they affect what we see. Two people with different mental models can observe the same event and describe it differently, because they've looked at different details"*. [23] (p. 160)

The growth of global warming and related climate change phenomena originated a few centuries ago at the start of the Industrial Revolution, but it was only a few decades ago—thanks to technical progress that allowed accurate and widespread surveys to be performed and information to be disseminated to all strata of society—that man became aware of the problem. A social alarm was generated that gave rise to a widespread movement in public opinion, accompanied by increasingly stronger actions, to convince policy makers to intervene with the utmost urgency [113]. Avoiding undue pessimism and not contemplating the risk of a world war, there is no doubt that the increase in global warming represents "*mankind's most urgent problem*".

Therefore, today, we talk and hear daily about "global warming" and "climate change", but not many of us are able to build appropriate mental models to understand these phenomena. In this theoretical paper, using the *logic* and *formal language* of systems thinking and observing reality from a sufficient "height", I built some models I believe can outline the system that produces global warming.

### *8.2. Three Fundamental Variables on Which the Models Proposed in This Study Are Based*

(I) I identified "global economic activity" as the "human machine" that produces global warming, translating this mental model into the formal Global Economic Activity Model (GEAM) (Section 3, Figure 3). Global economic activity produces, distributes, uses and consumes the goods and services necessary for man to survive and to raise his standard of living. Apart from human labor, the energy for production is provided by "machines" that require the consumption of fossil fuels that generate huge "volumes of greenhouse gases" that trap the heat from solar radiation, thereby increasing global warming. The GEAM allowed me to identify three *strategic areas* for outlining a control *strategy* by activating suitable levers (Section 4, Figure 4). The first area is represented by the investment and actions to contain greenhouse gas emissions produced by man; the second area relates to the changes in consumption habits to stimulate the demand for goods whose production, distribution, use and consumption minimize the processes that produce emissions; the third area regards the actions to abandon or modify polluting production processes in favor of those that minimize the contribution to the greenhouse effect.

(II) I observed that the *size* and *intensity* of global economic activity depends on the *size* and *quality* of the population; on the one hand, an increase in population will have to be sustained by a greater production of goods and services; on the other hand, more intense global economic activity will be necessary when the populations of emerging economies, with a reduced standard of living, low consumption and limited property, rightly aspire to an increase in the quantity and quality of their consumption and of the goods they possess, requiring greater production from global economic activity.

(III) Continuing with the logic of systems thinking, I considered natural phenomena activated by the same global warming trend with balancing or reinforcing loops, which could reduce or accentuate the dynamics of global warming. First, I devised a model (Section 6, Figure 6) to illustrate the positive effect on the natural control of global warming that would be generated by the slowdown of the Gulf Stream because of the melting of Arctic ice due to the increased temperatures around the world. Subsequently, I considered the negative effect of the acceleration of global warming produced by the following four very negative natural processes, also generated by global warming (Section 7, Figure 7): (a) the reduction in the expanse of ice and (b) the increase in forested areas in the north, which would reduce the albedo effect, limiting the reflection of sunlight, thus favoring the increase in global warming; additionally contributing, to a large extent, to this development is the warming of the oceans accentuated by (c) the proliferation of dark algae that retain heat due to radiation; finally, I considered the potentially disastrous effect that would result from (d) the thawing of the tundra and the consequent release into the atmosphere of large volumes of methane, no longer trapped in the ice, with the power to increase the greenhouse effect 30 times more than the increase due to $CO_2$ emissions.

### *8.3. A First Limitation of This Study: It Does Not Consider a Possible Population Control Strategy*

This paper has some limitations. The most relevant is that it does explore in more detail the effect a *control strategy for world population* would have on global warming. In fact, in countries where the population "ages", individual consumption falls, on average, with advancing age, thus slowing down global economic activity. A "young" population, on the other hand, accelerates consumption and wants to increase the stock of goods it possesses through an acceleration of economic activity. The paper does not analyze the interaction between these variables, nor does it address the problem of *population control* itself, a process that requires complex strategies that act differently depending on whether the population needs to be increased or reduced. An increase in population would require policies aimed at combating infant mortality, improving living conditions and health and favoring larger families by means of economic incentives, as was the case in Italy from the latest part of 1925 to the end of World War II. In the reverse situation, policies are needed to reduce the birth rate, given that no government could sensibly introduce acceptable measures to reduce the number of elderly people. It is interesting to consider how China has dealt with this problem over the past few decades. To reduce its population, laws introduced in 2001 imposed a mandatory "one-child policy" to control demographic growth, whereby families were prohibited from having more than one child, especially in rural areas [114,115]. This policy proved successful; the population decreased considerably, although it also aged, creating problems of sustainability. Therefore, the "one-child policy" was revised in December 2013 and, from 2014 onward, Chinese couples were allowed to have two children. To counteract the progressive aging of the population, it was necessary to increase the number of young people; for this reason, in May 2021, amendments were made to the "law on population and family planning" that allowed families to have a third child (a limit that will be abolished in 2025), since, otherwise, a sustained decrease would occur which would reduce the Chinese population to about 730 million people in 2100 [116]. To encourage the desire to have a third child, economic and social subsidies were introduced for families, such as kindergartens, schools, parental leave, etc. However, it will not be easy to increase the population in countries with thriving economies such as in China since young Chinese may be frightened both by the high cost of living for a large family, linked to education, and by the career prospects for parents.

### *8.4. The Specific Control Levers of Global Warming and Their Interactions*

Another important limitation of the paper is that it does not systematically examine the *specific control levers* of global warming that can be implemented or even imagined within the three strategic macro areas, also as a way of highlighting the difficulties and shortcomings of each measure. Beyond the examples presented in Section 5, I believe that even a brief analysis of specific (often local) measures, however interesting, would not be justified in a theoretical paper, given the fact that countries do not always agree on the measures to adopt. China, India, Russia and Indonesia, for example, are reluctant to abandon hard coal as an energy source and the major fossil fuel-producing countries are even planning to double their production, as recently stated in "The Production Gap Report" of the Stockholm Environment Institute.

> *"As countries set net-zero emission targets, and increase their climate ambitions under the Paris Agreement, they have not explicitly recognized or planned for the rapid reduction in fossil fuel production that these targets will require. Rather, the world's governments plan to produce more than twice the amount of fossil fuels in 2030 than would be consistent with limiting warming to 1.5 °C. The production gap has remained largely unchanged since our first analysis in 2019.".*

> *"According to our assessment of recent national energy plans and projections, governments are in aggregate planning to produce around 110% more fossil fuels in 2030 than would be consistent with limiting global warming to 1.5 °C, and 45% more than would be consistent with limiting warming to 2 °C, on a global level. By 2040, this excess grows to 190% and 89%, respectively"*. [117]

Moreover, there does not yet seem to be agreement on the objectives; in COP21, which took place in Paris in 2015, every country agreed to work together to limit the growth of global warming to well below 2 degrees, aiming at a target of 1.5 degrees. The latter limit, albeit with some reservations, was agreed upon by the countries that participated in the recent COP20 held in Rome in October 2021. However, it should be noted that the time limits within which the reduction in the use of coal must be achieved have not been agreed upon; the target is expected to be achieved by 2050, even though Russia has announced 2060 and India 2070 as target dates. The efforts of the decision-making countries seem to be focused on the *strategic lever* of the elimination of polluting fuels, in particular decarbonization, in global economic activity [109].

However, once this strategic objective has been established, some simulations on the timing of the implementation of the levers for this strategy would be useful. Consider, for example, the replacement of a fleet of traditional fuel cars with electric traction vehicles. Considering that about 1.2 billion cars are currently in circulation, of which 3.3 million are electric cars, and that, in 2019, 91.5 million vehicles were produced and sold, although with declines in some countries compared to the previous year [118], in theory, if all the cars produced were electric and the replacement occurred immediately according to annual availability, it would take 13 years to eliminate car emissions. However, this time should be lengthened, perhaps significantly, since we must take into account that the replacement would be gradual and not immediate for everyone, given the cost of new electric vehicles and the acceptance of this new means of individual transport, which requires charging times that are still too long. A promising prospect are *hydrogen cars*, which have been produced since 2014, with Toyota alone selling about 10,000 of them. They are perfectly efficient and safe, with a relatively low operating cost, but their widespread use is made difficult due to the very low number of hydrogen distributors. However, it must be considered that 98% of hydrogen is produced by steam methane reforming, which emits carbon dioxide [119]. Similar considerations must be made for the replacement of traditional boilers and kitchen stoves with zero-emission ones, which, today, are used in billions of homes and public and private locales. Since the goal of "zero-emissions", even if it concerns the entire planet, must necessarily be achieved through actions at the local level, the concept of "Net Zero Energy Communities" has been spreading. These are local communities, cities, or even entire regions which must seek to achieve the same global objective by acting on specific sources of emissions, such as transport, the heating of buildings and energy production, and agriculture and livestock [120]. Finally, it should be noted that most of the steps taken to change the quality of *energy consumption* must occur as part of global economic activity. Therefore, it is necessary to verify that the result of these measures does not reduce the benefits of the "productive machine", i.e., employment and wages, consumption, profits, taxes, investments and production (Figure 3).

### *8.5. Conclusions: Global Warming—Is It (Im)possibile to Stop It?*

I conclude this brief study by taking up the question in the title, "Global Warming: Is It *Possible* to Stop It?" The models developed do not provide an answer, because this depends on the actions that the various countries undertake; however, it is comforting to observe an awareness of the need for global and shared action. However, these models make it possible to identify the variables on which global warming depends and in which strategic areas it is necessary to intervene. The urgency of keeping the growth of global warming under control is recognized by all. The slogan that Boris Johnson launched at the COP26 conference in Glasgow is clear; "*It is one minute to midnight*" in the battle against climate change [121].

The second question in the title asks the following: “Global Warming: Is It *Impossible* to Stop It?” To answer this, the models also direct our attention to natural events outside the decision-making sphere, indicating that it could be it impossible, or at least very difficult, to control the phenomenon.

In both cases, it is not comforting to note that, even though the social alarm for global warming and climate change was triggered a few decades ago and all countries have agreed, in principle, to reduce emissions, today, there is still no *deliberate* strategy to counter the danger. Countries are still in a “work in progress” phase with proposals still to be fleshed out, also considering that many desired interventions require a long or very long time—one or two generations—for the implementation of control strategies, as well as huge investments many countries cannot afford. This makes any forecast difficult. However, it would be extremely interesting to analyze the times and costs needed to activate the different measures contained in the three macro strategic areas; however, these are times and costs that always depend on global economy activity. For now, these interesting themes are left to future investigations.

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## Appendix A. The Language of Systems Thinking

Systems thinking was introduced by Peter Senge in his important work, “The Fifth Discipline: The Art and Practice of the Learning Organization”. Senge adopted a simple and captivating language, accessible to all, that could be understood by a broad readership [23,122], recently formalized by [110]. Systems thinking is a powerful logical method and an effective formal language whose logic can be summarized as follows: if one wants to understand the “world”, it is necessary to observe and link the variables behind its phenomena so as to produce systems that are unitary and repetitive (often recursive) and whose workings are a function of the dynamics of its component variables while, in turn, influencing these same dynamics.

The most interesting and useful connections among the variables that make up “reality” are not the “linear” ones—characterized by *chains of causes and effects*—but the “circular” ones, the *feedbacks* and *loops*, which not only connect but also interconnect the elements, which are not only dynamic but also interactive.

Systems thinking employs a formal though simple language, representing the cause-and-effect relations using arrows that unequivocally correlate their variations. The tail of the arrow indicates the causal (input) variables, while the head shows the effect (output) variables.

If increases or decreases in variable X correspond to increases or decreases in variable Y, the two variables have the “same direction of variation” (“**s**”) (left arrow below). X and Y have the “opposite direction” (“**o**”) if increases or decreases in the former result in corresponding decreases or increases in the latter (right arrow). The cause-and-effect relations are represented as in Figure A1.


**Figure A1.** The two cause-and-effect relations.

There is no limit to the number of connected variables forming a *causal chain*.

If X and Y are interconnected in two opposite directions, they form a *circular link*, a *loop*, or a *ring*.

There are only two basic types of loops.

1. *Reinforcing* loops (**R**), whose action generate a *mutual increase* or *reduction*—in successive repetitions of the system's cycle—in the values of the two linked variables, which have an identical *direction of variation*, i.e., "**s** and **s**", or "**o** and **o**", as shown in Figure A2.

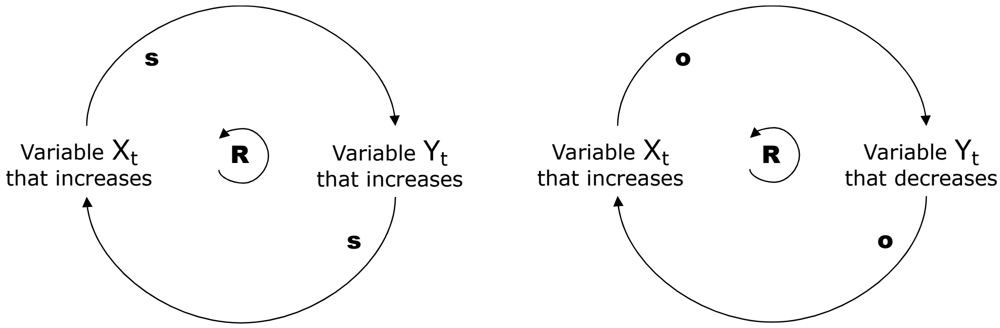


**Figure A2.** Two forms of *Reinforcing* loops.

2. *Balancing* loops (**B**), whose function is to *maintain relatively stable* the values of the linked variables, which are connected by a different *direction of* variation, i.e., "**s** and **o**", or "**o** and **s**", as in Figure A3.

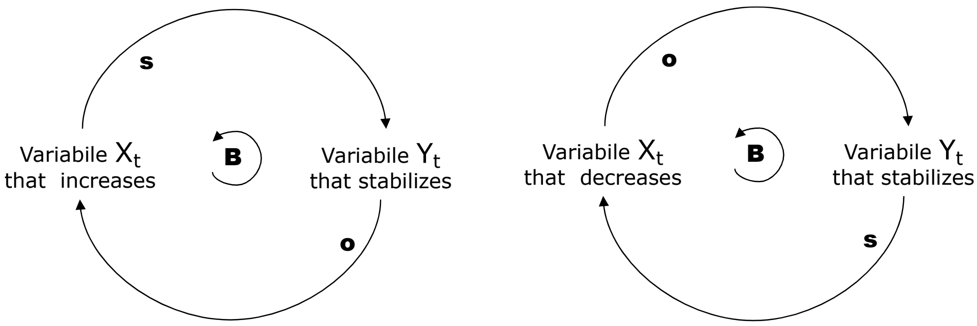


**Figure A3.** Two forms of *Balancing* loops.

There is no limit to the number of interconnected variables.

A system of loops in which all variables are linked by arrows, without an initial and final variable, is defined as a *causal loop* diagram [123,124]. Systems thinking is not only a technical language but also a discipline.

> "*... a developmental path for acquiring certain skills or competencies. [ ... ] To practice a discipline is to be a lifelong learner. You "never arrive"; you spend your life mastering disciplines*" [23] (p. 101)

Systems thinking models are typically suited to qualitative research into the systems they represent; they offer an understanding of their structure and allow us to examine the direction of the dynamics of the variables. In quantitative terms, systems thinking uses the simulation procedures of system dynamics, a discipline and technique that dates to Jay Forrester and his major work titled "Industrial Dynamics" (1961). Recently, Forrester has provided the following definition of system dynamics:

> *""System dynamics" is a professional field that deals with the complexity of systems. System dynamics is the necessary foundation underlying effective thinking about systems. System dynamics deals with how things change through time, which covers most of what most people find important. System dynamics involves interpreting real life systems into*

*computer simulation models that allow one to see how the structure and decision-making policies in a system create its behavior"* [125] (p. 1)

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