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Environmental Determinism vs. Social Dynamics: Prehistorical and Historical Examples

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Abstract: Environmental determinism is often used to explain past social collapses and to predict the future of modern human societies. We assess the availability of natural resources and the resulting carrying capacity (a basic concept of environmental determinism) through a toy model based on Hurst–Kolmogorov dynamics. We also highlight the role of social cohesion, and we evaluate it from an entropic viewpoint. Furthermore, we make the case that, when it comes to the demise of civilizations, while environmental influences may be in the mix, social dynamics is the main driver behind their decline and eventual collapse. We examine several prehistorical and historical cases of civilization collapse, the most characteristic being that of the Minoan civilization, whose disappearance c. 1100 BC has fostered several causative hypotheses. In general, we note that these hypotheses are based on catastrophic environmental causes, which nevertheless occurred a few hundred years before the collapse of Minoans. Specifically, around 1500 BC, Minoans managed to overpass many environmental adversities. As we have not found justified reasons based on the environmental determinism for when the collapse occurred (around 1100 BC), we hypothesize a possible transformation of the Minoans’ social structure as the cause of the collapse.

Keywords: water–energy–food nexus; Minoan civilization; sustainable development; social structure



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“ . . . it is not famine, not earthquakes, not microbes, not cancer but man himself who is man’s greatest danger to man . . . ”

Carl Jung [1]

1. Introduction

Hypotheses of social collapses typically constitute scenarios about the environmental and societal conditions. The researcher’s imagination is the main tool to explain the process of the collapse. For these reasons, theories of social collapse have an intuitive charm but ambiguous significance [2]. However, are the hypotheses of the conditions close to reality? Would people in the past react as a modern researcher thinks they would do?

Ancient Greek philosopher Plato in his emblematic book *Republic* concludes that societies are like living creatures, and their existence also predicts their death. Quoting from the original text [3]: “ ἀλλ’ ἐπεὶ γενομένῳ παντὶ φθορὰ ἐστὶν, οὐδ’ ἡ τοιαύτη σύστασις τὸν ἅπαντα μενεῖ χρόνον, ἀλλὰ λυθήσεται. . . . ” (but, seeing that everything which has been born has also an end, even a constitution such as yours will not last for ever, but will in

time be dissolved). Plato describes social organization, justice and culture as main issues for thriving societies [4].

Many scientists consider that physical environment predisposes societies and states toward particular development trajectories. These aspects have been formulated in a school named *environmental determinism* [5].

Environmental determinism is not a new idea. It was introduced by Thomas Robert Malthus (1766–1834) in 1798 [6]. It was used to justify colonization [7–9], fascism [10] and Lamarckism [11,12], describing how tropical climates encouraged generally degenerative societies, while the frequent variability in the weather of the middle and northern latitudes led to stronger work ethics and civilized societies. Environmental determinism was recovered by Eugenicists and Neo-Malthusians in the 1950s in the notion of “Carrying Capacity” [13–20].

Lately, environmental determinism is used to formulate a holistic view of world history. In the book *A Green History of the World: The Environment & the Collapse of Great Civilizations*, Poline was trying to “probe . . . the extent to which the environment has shaped human history” [21,22]. Many researchers are following his perceptions [23–27].

In the early 20th century, more than 50 years before theories of climate change became trendy [28], Ellsworth Huntington connected the demise of civilizations with climate changes [29]. Many researchers view climate change or deforestation [30–40] as the main reasons for social collapses in the past. Related research predicts the future of world population growth in relation to the parallel deforestation process [41].

In some cases, the climate impacts of volcanic eruptions are studied. For example, Gao et al. [42] asserted that they can act as ultimate and proximate causes of Chinese dynastic collapse. While they emphasize the correlation between environmental factors and social dynamics, nevertheless, they note that:

Even in cases of collapse, that some dynasties persisted for up to a decade post-eruption while others collapsed more rapidly suggests the complexity of the underlying causal contributions and the inadequacy of monocausal or environmentally deterministic interpretations.

Other researchers, based on archeological data, do not confirm environmental determinism. Senan et al. [43] note:

. . . in contrast to the steady population growth usually assumed, the introduction of agriculture into Europe was followed by a boom-and-bust pattern in the density of regional populations. . . . we investigate the relationship between these patterns and climate. However, we find no evidence to support a relationship. Our results thus suggest that the demographic patterns may have arisen from endogenous causes.

Other approaches do not include the environment as a fundamental cause of the collapse. Through a neo-Platonic view, Tainter considers that societies are complex systems [44], and complexity is a necessary element for their growth. A dynamic crisis and collapse are contained in every growing social structure, as complexity will reach a limit where it cannot be managed [45].

Other approaches emphasize the point that civilizations are not quantities but also qualities, as they contain cultural values. The ideas of cultural aspects in the dynamics of societies, moral decline and related issues were first formulated by the Islamic historian Ibn Khaldun (1332–1406) [46], who recognized the periodic rise and fall of dynasties as macrostructures in the history of civilizations. The Western interest in this mechanism of collapse was formulated by Edward Gibbon (1737–1794) [47], who attributes, as does Khaldun, the collapse of the Roman Empire to moral decline.

Summarizing the above, upheavals in social stability and continuity can be said to be due to socio-political disorganization, economic weakness and environmental or demographic trends. Changes in social dynamics appear as long-term fluctuations, first organizing, then expanding and integrating, before sinking into disorder. The scale of the

collapse, the timeframes involved, the key elements that fail and whether the outcome is catastrophic or ultimately allows for restructuring remain open questions [48–53].

Section 2 of this paper presents a toy model explaining the mechanisms of the collapse through the view of environmental determinism adopting Hurst–Kolmogorov dynamics. In Section 3, we analyze the multipliers of social dynamics and their role, and in Section 4, we present examples where environmental determinism fails to explain the cause of collapse. In addition, we note that environmental determinism also fails to predict the evolution of modern societies.

In Section 5, we describe the Minoan civilization, which had an admirable social structure, impressive technology, culture and infrastructure. It dominated in the wider area of the Aegean Sea between about 3200 to 1100 BC, when it suddenly collapsed [54,55].

Section 6 overviews the current theories of the Minoan collapse, and in Section 7, these theories are evaluated; in Section 8, they are discussed.

2. Methodology

At the beginning, humans survived, perpetuated and spread as hunter gatherers, dominating the environment, reaching a relative equilibrium [56] and displaying remarkable resilience [57]. The possibility of human clustering [58,59] was very small, since man needed large areas to meet nutritional needs [60]. The great step toward civilization was primarily due to the capability of human clustering through language and technology. Communication (hence, social organization) and technology made humans more and more efficient, giving great clustering potential [61].

Human survival presupposes the utilization and exploitation of the water–energy–food nexus. The survival limits of humans are: 7 days at most without water, about 45 days without food [62] and a variable period without energy depending on the environmental conditions (e.g., when it is cold, more energy is needed). Thus, food, water and energy require constant replenishment. Hence, the nexus is the human “prey” [63]. In prehistory, predators of humankind were the big animals. In civilized societies, notable predators are the mosquito, to which one million deaths per year [64] are attributed, and pathogens, such as the bacterium *Yersinia Pestis* (known as Black Death), responsible for an estimated reduction in the world population by c. one-third in the 14th century [65].

In the following paragraphs, we will explain the aspects of environmental determinism in terms of carrying capacity, considering Hurst–Kolmogorov dynamics in natural resources, technology, trading, storage and social dynamics in a toy model to explain the mechanisms of collapse.

2.1. Lotka’s Model

Alfred Lotka (1880–1949) showed how species survive in a long-term prey–predator cycle [66,67]. His model describes the dynamics of competition between two species, say, wolves and rabbits. In general, prey and predators achieve balances according to their ability to survive and renew. The population is limited when there is no prey available and increases when there is plenty. The populations change throughout time according to the pair of equations:

$$\frac{dx}{dt} = \alpha x - \beta xy \quad (1)$$

$$\frac{dy}{dt} = \delta xy - \gamma y \quad (2)$$

where x is the population of prey, y is the population of predators, α , β , γ , δ are parameters describing the interaction of the two species. Figure 1 is a depiction of model outputs.

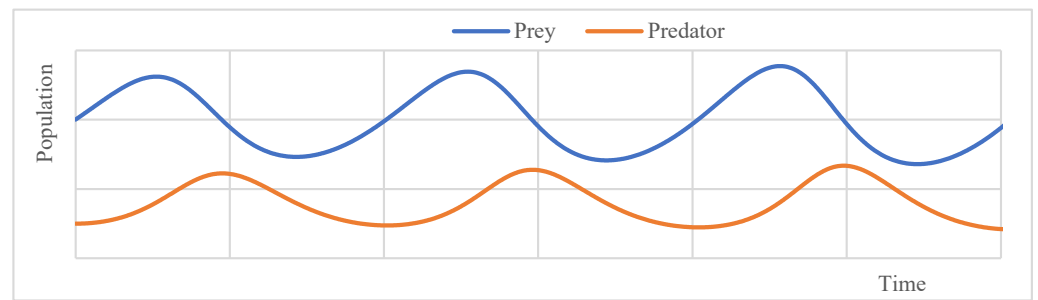


Figure 1. Example of Lotka's model.

2.2. Carrying Capacity

After humans managed to face the threats of big animals, they did not have systematic predators to interact with. As water, energy and food are necessary for their survival, we consider them as their prey [68].

In order to understand the meaning of carrying capacity, we create a toy model. In this, we imagine, for example, a group of people trapped in an island for 1000 years where there is only a spring. The annual outflow of a spring can be treated as a random variable, following, for example and for simplicity, a Gaussian distribution. The carrying capacity of a place will be related to the minimum flow, which could support a specific number of people, and we assume that the system would find an equilibrium around this value (Figure 2).

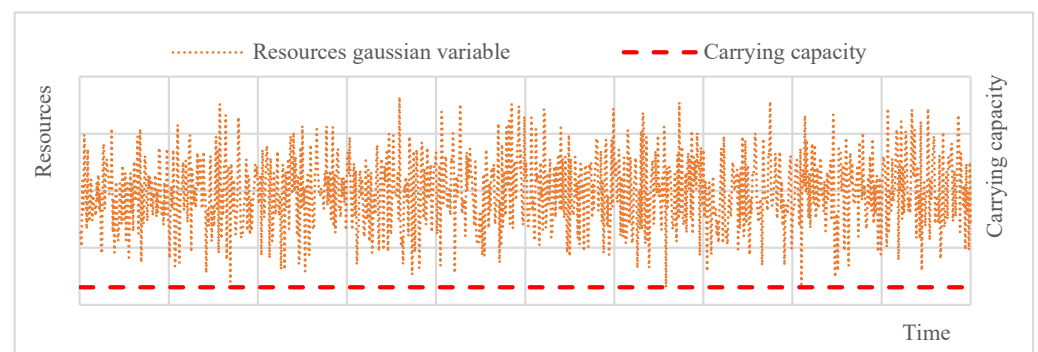


Figure 2. Toy model: the concept of environmental determinism. Outflows of the fountain follow a Gaussian distribution. Red dashed line shows the carrying capacity of the population.

However, we note some interesting limitations in the approach of carrying capacity:

1. The distribution of natural resources (especially ones related to water resources and management and inter-connected with food and energy) does not follow a white-noise behavior (i.e., with identically distributed and independent increments) and is better simulated by the so-called Hurst–Kolmogorov dynamics [69].
2. Humans have abilities to overlap these gaps through adaptation.
3. We have to consider including the dynamic of societies.

2.3. The Role of Hurst–Kolmogorov Dynamics in Environmental Determinism

An important property of natural phenomena is that they follow the Hurst–Kolmogorov (HK) behavior, also known as long-term persistence (LTP). It seems that in natural systems, randomness and predictability are intrinsic and can be deterministic and random at the same time, depending on the prediction horizon and the time scale [70]. In particular, all these processes are characterized by high unpredictability due to the clustering of events.

This behavior of natural systems was first identified in nature by H.E. Hurst in 1951 while working at the River Nile, although its mathematical description is attributed to A.

N. Kolmogorov who developed it while studying turbulence in 1940. Koutsoyiannis [69] named this behavior as Hurst–Kolmogorov dynamics (HK) to give credit to both pioneering scientists [71–74]. Interestingly, this behavior has been identified in global-scale key hydrological-cycle processes through the analysis of thousands of stations [75] and can also be observed in social parameters, such as in war frequency in China, which are related to the volcanic activity [42].

Although in HK dynamics the marginal distribution of the process may be arbitrary, the most commonly used distribution is the Gaussian one, which results in the well-known fractional Gaussian noise, described by Mandelbrot and van Ness [76], i.e., the power-law decay of variance as a function of scale $\gamma(k)$ is defined for a process [77]. The HK behavior is quantified by the Hurst parameter H ($0 < H < 1$). In the simplest case, the variance $\gamma(k)$ of the process at timescale k , known as a climacogram, is given by

$$\gamma(k) = \frac{\lambda}{(k/\Delta)^{2(1-H)}} \quad (3)$$

where Δ is a characteristic timescale, and λ is the variance at this time scale. For $0 < H < 0.5$, the HK process exhibits an anti-persistent behavior, $H = 0.5$ corresponds to the white noise process, and for $0.5 < H < 1$, the process exhibits LTP (clustering).

Therefore, to account for the effect of the non-white-noise behavior of the spring outflow in our toy model, we simulate the spring outflow based on the HK model (with, for example, $H = 0.8$) and by following a Gaussian distribution (described earlier) through a stochastic synthesis algorithm, and in particular, through the symmetric moving average (SMA) scheme [78,79]. Figure 3 shows a so generated timeseries. An environmental determinist would likely say that the society would collapse four times (red triangles).

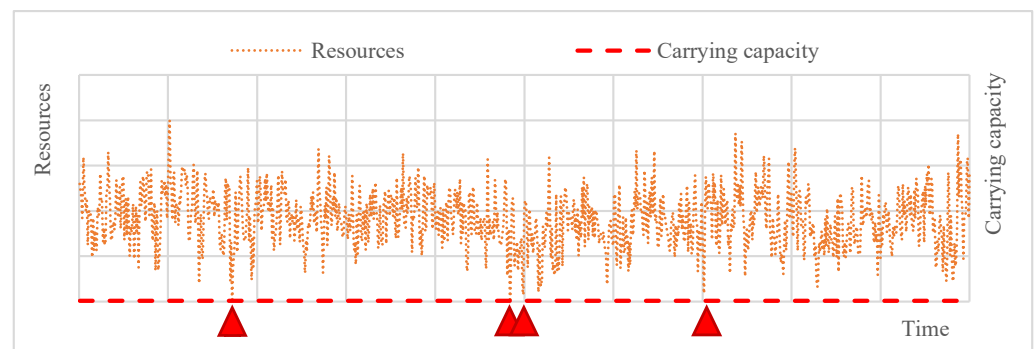


Figure 3. Toy model: The concept of environmental determinism with HK dynamics with $H = 0.8$. Outflows of the fountain follow Gaussian distribution. Red dash line shows the carrying capacity of the resources and red triangles show the phases of collapse.

2.4. The Role of Technology and Trading in Environmental Determinism

In prehistory, there is a strong possibility that this type of collapse could not affect societies that were never “organized” in the first place. These societies were flexible; they did not have infrastructures or stable wealth, and they could move to other places to find resources. This is how we could justify the switch from more socially structured and sedentary societies to smaller-scale, pastoralist and mobile societies, with some societies constantly switching between both types of economy. This type of adaptation some would even call “resilience”.

With agricultural evolution, human societies handled the water–energy–food nexus more efficiently, and they could possibly survive these gaps facing the threats of recessions in their settlements. If our group of people on an island dig a well or travel to another

island close by to bring water from there, they would have more water. In order to indicate that, we add a constant quantity z at each value in the time series:

$$\underline{x}' = \underline{x} + z \tag{4}$$

Note that we use underlined symbols for stochastic variables (Dutch notation).

This model is depicted in Figure 4. An environmental determinist would consider that the population could be increased. However, ancient sedentary societies would be vulnerable to this phenomenon, as these societies would thrive when there were plenty of resources, but HK dynamics predicts a systemic crisis every time resources are restricted.

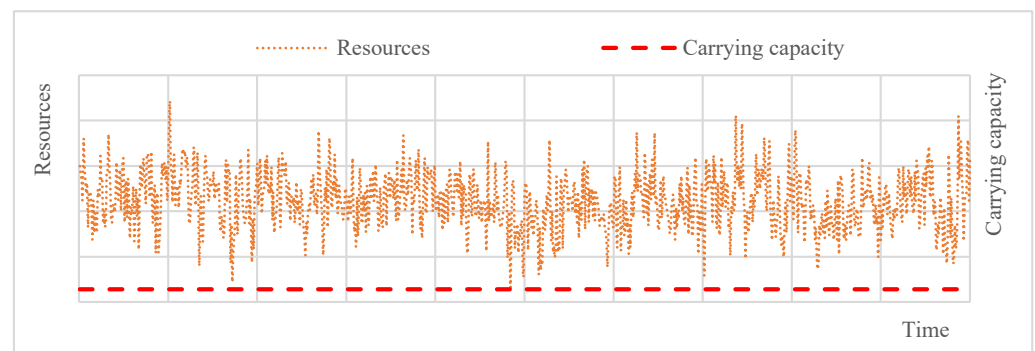


Figure 4. Toy model: The concept of environmental determinism with HK dynamics adding a technological step. Red dash line shows the carrying capacity of the resources.

2.5. The Role of Storage in Improving Carrying Capacity

Since early times, people realized how nature works, i.e., they developed a practical understanding of what today we call HK dynamics. Therefore, they considered that they have to store the resources when there was abundance in order to use them when there was scarcity. The first written mention of this concept was recorded in the Bible where Joseph advised Pharaoh to store the food in wealthy years, as he predicted that dry years would come [80]. HK dynamics has also been called the Joseph effect [69].

In our toy model, if we consider that people make a small dam, and water withdrawals are dependent on the availability of the resources, the system will become more stable, increasing its carrying capacity and avoiding collapses. The process can be modeled by the following equations [81,82]:

$$\underline{S}_T = \max (0, \min(K, \underline{S}_{T-1} + \underline{x}_T - \underline{R}_T)) \tag{5}$$

$$\underline{R}_T = a\underline{S}_{T-1} \tag{6}$$

where T is time; \underline{S}_T is the stock in the reservoir; \underline{x}_T is the inflow; \underline{R}_T is the withdrawal considered proportional to the stock; a is a constant determining the release; and K is the storage capacity.

Figure 5 depicts the effect of available resources with the use of storage.

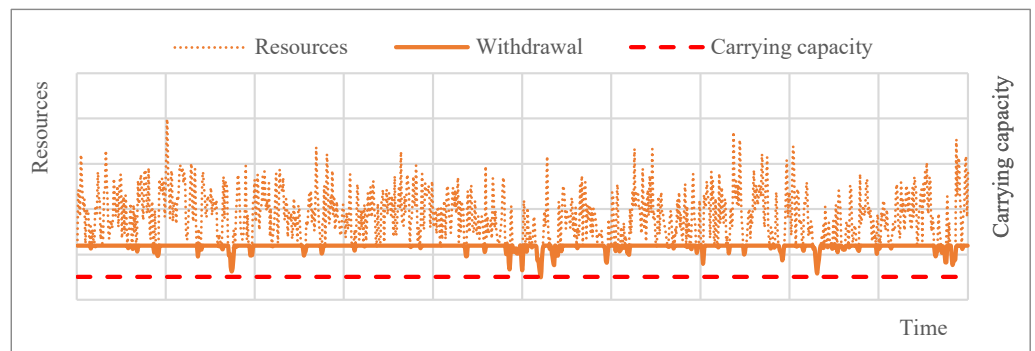


Figure 5. Toy model: The concept of storage with HK dynamics. Red dash line shows the carrying capacity of the population.

2.6. *The Role of Growth and Sustainability of Resources in Environmental Determinism*

If we combine in our toy model the advantages of technology, trading and storage, increasing them in time, we could model the evolution by the following equation, assuming linear changes in time of storage capacity K_T and resources x'_T , as follows:

$$K_T = (1 + \epsilon T)K_0 \tag{7}$$

$$x'_T = \underline{x}_T + \zeta T \tag{8}$$

where ϵ and ζ are constants determining the linear relationships. The results of the new toy model are depicted in Figure 6.

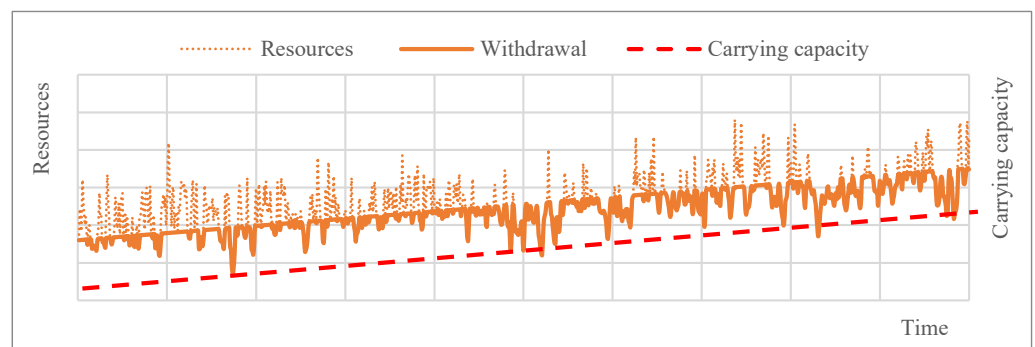


Figure 6. Toy model: The concept of carrying capacity with HK dynamics where storage and technology are increasing.

However, if the rhythm of consumption increases, even if we have the ability to increase storage, we note a dynamic of collapse. If we consider the constant a in Equation (6) (the proportion of the storage released) an increasing function of time, i.e.,

$$a = a_0 + \eta T \tag{9}$$

where η is a constant, then we obtain the results depicted in Figure 7.

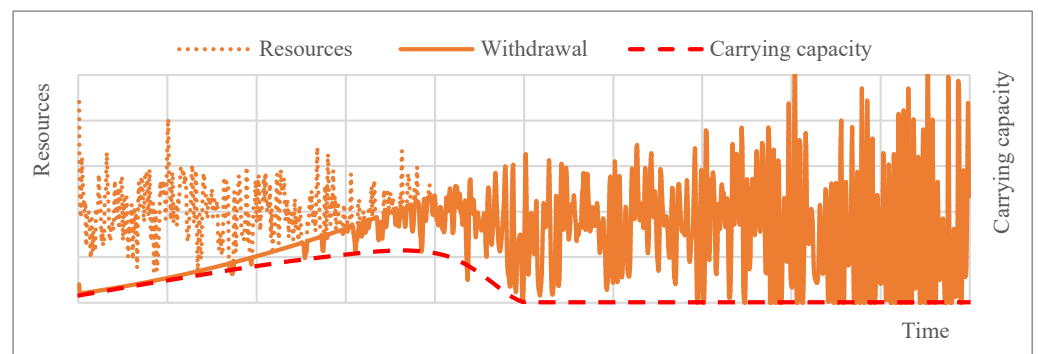


Figure 7. Toy model: The concept of environmental determinism with HK dynamics where storage and technology are increasing, but the available resources are not consumed sustainably.

2.7. An Entropic View of Growth and Recession

In the 21st century, a new scientific field has developed, econophysics, which combines socio-economic dynamics with the laws of physics. Social prosperity presupposes social constitution, which in turn presupposes social stratification and development. Social stratification together with the economic aspects of society are the factors that determine entropy.

Although in physics entropy is often widely used as a measure of disorder, its universal character, stemming from its stochastic definition, features it as a measure of uncertainty. Together with the accompanying principle of maximum entropy, it forms an excellent tool to describe the dynamics of societies.

Koutsoyiannis and Sargentis note [83]:

According to its standard definition . . . entropy is precisely the expected value of the minus logarithm of probability. If this sounds too difficult to interpret, an easy and accurate interpretation is that entropy is a measure of uncertainty. Hence, maximum entropy means the maximum uncertainty that is allowed in natural processes, given the constraints implied by natural laws (or human interventions).

Mathematically, for a continuous stochastic variable x , the entropy Φ is defined as

$$\Phi[x] := E \left[-\ln \frac{f(x)}{\beta(x)} \right] = - \int_{-\infty}^{\infty} \ln \frac{f(x)}{\beta(x)} f(x) dx \quad (10)$$

where $\beta(x)$ is a background measure and can be any probability density. Typically, it is a Lebesgue density, i.e., constant, and it is assumed $\beta(x) = 1/\lambda$, with λ being a monetary unit [83]. If the stochastic variable x is the income of people, then entropy reflects the uncertainty in the income distribution. From the principle of maximum entropy, given the constraints we have about income, we can determine the probability density $f(x)$, which determines stratification in the society.

From an entropic viewpoint, we note that when the real average of the people's income increases (growth), the entropy Φ also increases. Conversely, if the real average decreases (recession), entropy Φ decreases too. In this respect, it turns out that entropy is also a measure of society's wealth. In a recession phase, as entropy decreases, societies flow in an unstable phase. This aspect can also be connected with social crises in the abrupt limitation of resources (recession due to environmental causes) by the HK dynamics or with non-sustainable consumption of resources.

In addition, we have to note that as growth increases the society's entropy, it also increases the uncertainty, and, according Tainter, growth means an increase in sociopolitical complexity. In his book *The Collapse of Complex Societies* [44] Tainter notes:

Collapse is a political process . . . A society has collapsed when it displays a rapid significant loss of an established level of sociopolitical complexity.

Complexity is indispensable for growth. Max Roser notes [84]:

In a positive-sum economy your living standards are not determined by the productivity of your piece of land, but by the productivity of the economy that you are part of—the goods and services that you rely on are produced in a large-scale collaboration of millions of workers. Your economic well-being depends on them.

An increase in the pair of those variables (uncertainty and complexity), which are interconnected, is also related to the dynamics of collapse.

2.8. An Entropic View of Social Dynamics and Stratification

It would be oversimplification if we considered that the available resources are distributed equally between the members of society [85]. An interesting, related paper by Kohler et al. [86] shows that the progress in technology and available energy (use of animals) in ancient times is related to the increase in inequality. Same conclusions are delivered by Atkinson for modern economies [87]. Recent studies [60,83] draw similar conclusions, presenting the dynamics of stratification in societies with an entropic approach [88]. Roser and Ortiz-Ospina [89], based on the publication of Milanovic et al. [90], visualize how inequality increases with higher average income.

To frame the results within the context of a typical economic analysis of income distribution, we employ two well-known measures of socio-economic inequality, the Lorenz curve [91–94] and the Gini coefficient [95–97].

As usual with economic data, we follow the convention of expressing the income distribution in tenths of the share x (%) of people from the lowest to the highest income vs. share y (%) of the income earned. In Figure 8a, the rectangles show the case of all people having the same income, and the diamonds show the case of extended inequality, i.e., if the last tenth of share (%) has most part of the wealth (Pareto distribution). Figure 8b shows the Lorenz curve, which is the plot of the cumulative share of income vs. the corresponding cumulative share of the population. In the case of a perfect socio-economic equality, the curve is a straight line (plotted in rectangles), and the diamonds show the case of extended inequality. From the Lorenz curve, we can calculate the Gini coefficient, which is a measure of socio-economic inequality estimated as $G = A / (A + B)$, where A is the area that lies between the line of equality and the Lorenz curve, and B is the area between the Lorenz curve and the horizontal axes. Values of G tending to 0 indicate equality, whereas values closer to 1 indicate inequality.

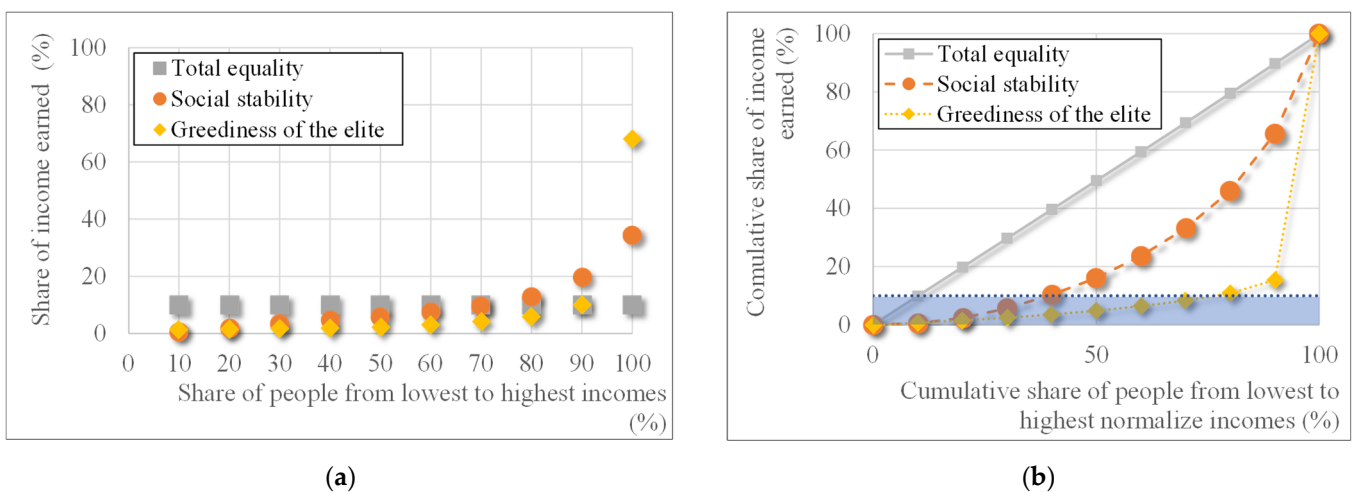


Figure 8. Different types of distribution of wealth. Gray rectangles show total equality with Gini coefficient equal to 0; orange circles show exponential distribution with Gini coefficient equal to 0.5; yellow diamonds show power-type Pareto distribution (greediness of elite) with Gini coefficient equal to 0.7 (a) Share of wealth (b) Lorenz curve (blue area represents a recession 10%).

The entropic approach provides another way to evaluate inequality. While for constant background density equal to the inverse of the monetary unit the entropy provides a measure of society's wealth, if we change the background measure to the value $1/\mu$, where μ is the mean income, the thus calculated entropy is a measure of inequality. Calling the latter quantity *standardized entropy* and denoting it as $\Phi_\mu[x]$, we obtain [83]:

$$\Phi_\mu[x] = \Phi[x] - \ln \frac{\mu}{\lambda} \quad (11)$$

The plots of share of income and Lorenz curve shown in circles in Figure 8a,b correspond to the exponential distribution (Gini coefficient equal to 0.5), which yields an entropic index of inequality $\Phi_\mu[x]$ equal to 1 (maximum value of $\Phi_\mu[x]$) [83]. This corresponds to a stable social structure (maximized entropy-stable distribution). In the aforementioned cases of more equality, as well as the case of greediness of the elite (Pareto distribution), $\Phi_\mu[x]$ is reduced [83].

If social organization disintegrates [98], civilization will collapse. It is believed that moral decline and extreme stratification are some of the contributing causes, while the contribution of technology, trading and storage is less obvious. For example, in the above-mentioned Biblical story, if in the years of abundance, the Pharaoh kept all the surplus of the storage in order to satisfy the elite and trade it or make useless symbols of power, social crisis, starvation and collapse would be the one-way outcome.

A recession phase means a deformation of stratification. A general consideration is that the more vulnerable population in this phase is the elite [30], as their existence is based on the surplus, which is restricted at this time. However, it is exactly this surplus, which gives the elite the resilience in recession phases and the potential for oppressing the poor with multiple mechanisms.

Figure 8b tries to show how a phase of recession would affect the poor if the rich would not redistribute the wealth, in a simplified manner. The blue area shows the impacted people when resources are reduced by about 10%. In the Pareto distribution (for example in Ancient Egypt where Gini coefficient is estimated close to 0.7 [99]), about 80% of the population would be impacted. In the exponential distribution, about 40% would be impacted. In a totally equal society, as all the people are equal, one could assume that this would impact 100% of the population.

History shows that stratified societies were distinguished and lasted for a long time when they prioritized a better way of living for members of the society, and this example shows the capacity of the elite to save the society from collapse by redistributing wealth. By evolving Lotka's model, Motescharrei et al. [100] developed the model HANDY, which includes human and natural dynamics, showing how social stratification is involved in societies' collapse.

2.9. Summary of Methodology

The above considerations allow us to summarize the following methodological issues:

1. The availability of natural resources follows HK dynamics, which results in recessions and expansions in multiple phases.
2. Humans have creative abilities, such as technology and storage, to overcome the phases of recession.
3. If the rate of consumption exceeds the technology-enabled resources, the society has a potentiality of collapse.
4. The entropic approach to social dynamics suggests that:
 - (a) When the real average of the people's income increases (growth), entropy Φ is increased, and when the real average decreases (recession from environmental or social causes, including type of consumption), entropy Φ is decreased.
 - (b) The growth of civilization also means an increase in complexity. As entropy is a measure of both uncertainty and complexity, growth means an increase in both variables, which gives a potentiality of collapse.

- (c) Equal distribution of wealth means an unstable social structure and less total wealth. From the entropic viewpoint, in this extreme case, entropy tends toward $-\infty$ [83].
 - (d) The elites have the capacity to alleviate recession phases. However, the greediness of the elites means that society may fall into decadence. From the entropic viewpoint, in this extreme case, entropy tends toward zero [83].
 - (e) Exponential distribution of wealth corresponds to the optimum stable social structure and corresponds to the maximum entropy.
5. The natural tendency of entropy is to increase (provided that energy does not decrease). Every time we note entropy decreases, contrary to its natural tendency, societies switch to an unstable phase [83].

A depiction of these methodological issues is shown in Figure 9.

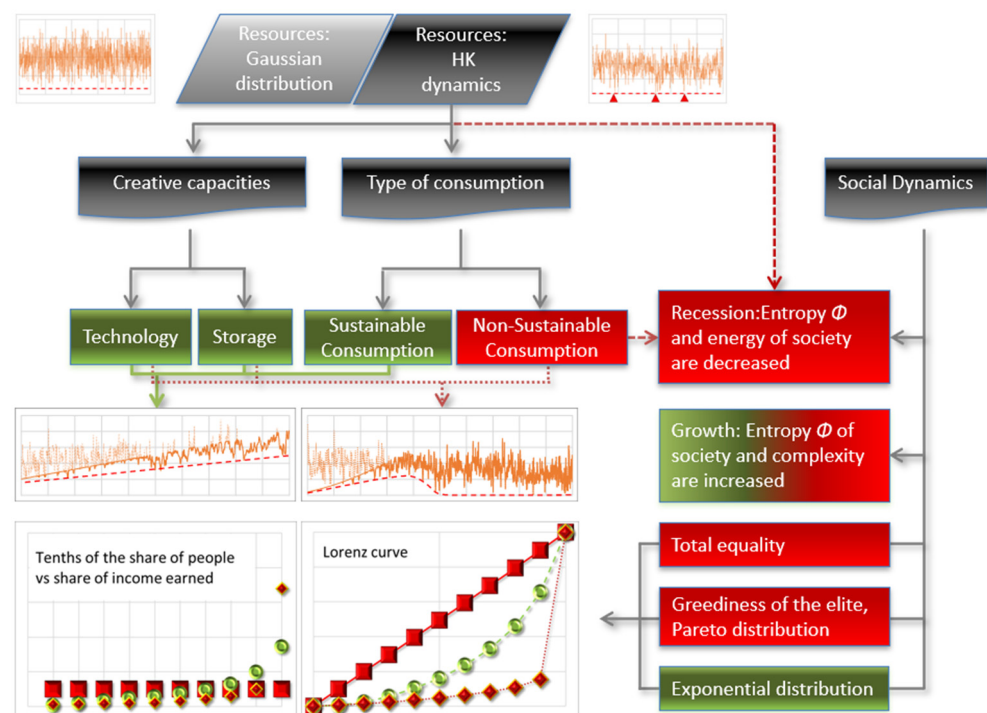


Figure 9. Summary of methodology. Green color shows aspects of a flourishing society; red color shows aspects with a dynamic of collapse.

3. The Multipliers of Social Dynamics

3.1. Optimizing the Prey of Water–Energy–Food Nexus

Water and food: Controlling water availability is a key factor. Advanced hydraulic works served as a multiplier of civilization, as an irrigable area can produce multiple amounts of food vs. those of a non-irrigable area [101].

There are various theories about the connection of social dynamics with hydraulics. An interesting theory was developed by Karl August Wittfogel [102]. He assumes that hydraulic works are the basis for human society, but they need management and, according to his theory, this justifies social stratification and despotism, as there is a need for special knowledge and a bureaucratic management of resources and infrastructures by an elite.

However, what is also worth noting is the role of hydraulics as a peace maker. Civilizations with large hydraulic works and infrastructure, which improved the quality of life, as demonstrated by the Romans [103] and the Chinese [104,105], endured and prevailed for a significant time [106]. On the contrary, civilizations based on state-of-the-art military technology, such as those of Alexander the Great [107] and the Mongols [108], did not last quite as long (Figure 10).

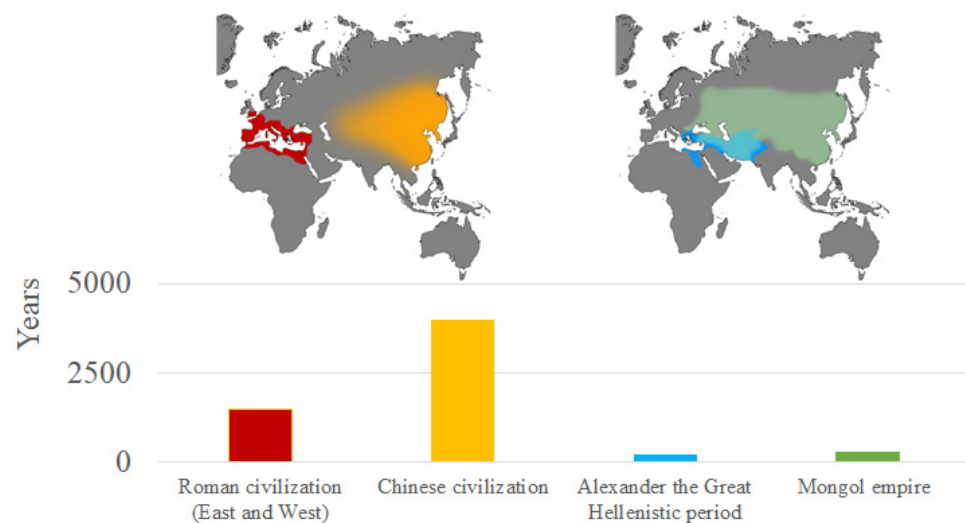


Figure 10. Roman, Chinese, Alexander the Great-Hellenistic Period, Mongols. (**Upper**): Expansion of civilizations; (**Lower**): Duration of civilization based on civil infrastructures (Roman, Chinese) and duration of civilization based on state-of-the-art military technologies (Alexander the Great-Hellenistic Period, Mongols). Geographical areas are delineated approximately.

Energy: The agricultural revolution was a pivotal advancement for the development and durability of civilization. The adoption of new techniques in agriculture and the use of animals allowed humans to cluster about 100 times more at a cost of about 3 times more energy per person to produce food than when living as hunter gatherers [60].

The importance of energy becomes clear if we consider that since the Homeric times, the cattle's size signified the wealth of a person. The unit of wealth measurement in the Roman Empire was an animal's head (Latin: *capis*; Greek κεφαλή), which bequeathed to us the term capital [60] (Greek κεφάλαιον). In 1909, Wilhelm Ostwald first noted that energy consumption is correlated with life expectancy [109]. Recent data analysis confirms his observations [106].

3.2. The Role of Social Organization

Since the creation of science in the 6th century BC [110], improvements in the quality of life ensued based on progress of science, technology and medicine [111], fostering an increasing life expectancy [112–115].

All of the above (science, technology, medicine) are optimized with division of labor, social organization and economy. The necessary condition for them is the continuity and functioning of the educational system. Communication–cooperation (interactions) and economies of scale helped scientific research and technology to create infrastructures and low-cost production, which are the basis for flourishing societies [116–120].

Many approaches to social organization and the formation of social stratification have been introduced in recent history. The widely known ones are those of Adam Smith (1723–1890) [121,122], David Ricardo (1772–1823) [123,124], Thomas Robert Malthus (1766–1834) [6], the Social Darwinists (late 1800s) [125,126] Karl Marx (1818–1883) [127,128], John Keynes (1883–1946) [129], Milton Friedman (1912–2006) [130], Friedrich Hayek (1899–1992) [131], Zoya Hasan [132] and Walter Rodney (1942–1980) [133]. Recently, new ideas have been put forward. Thus, Tim Jackson and Serge Latouche introduced the concepts of “prosperity without growth” [134] and “de-growth” [135,136], respectively.

4. Widely Known Case Studies of Collapse in the View of Environmental Determinism

4.1. Environmental Determinism in the Past

Maya: Heinberg [137] reported that complex societies that are limited to a single bioregion, such as the Classic Maya civilization, are more likely to collapse quickly as a

result of damage to the ecosystem, while those of greater geographic extent typically persist for decades or centuries longer [138].

During the 8th–9th Century, the Mayans deforested large areas [139] in order to clear the land for agriculture and burned trees to make lime mortars for their complex constructions [140] (Figure 11a). In a relevant study, it is speculated that the scale of deforestation broke down the hydrological cycle and was the reason for the drought that followed in the area during this period [141]. The lack of forest cover contributed to soil depletion and erosion.

Obviously, civilizations often face many different types of natural disasters and usually, after a recessionary cycle, they manage to recover. For example, in the preclassical phase, the Mayans had managed to survive two long-term droughts, which were estimated by the analysis of stalagmites from the Yucatán [142,143]. Furthermore, in the classical phase, the Mayans had to deal with eight severe droughts of 3–18 years in length between 750 and 1050 AD [144–147]. Data show that, in these periods, growth was stopped, but the important fact is that the Mayans were able to recover many times. Recovery depends on the kind of recession, but certainly, it requires proper social organization and coordination.

The Mayans did not just disappear, but they rather abandoned their cities. As crops failed because of drought, farmers and artisans emigrated to escape starvation in a wider area. If we consider that societies in the new world were more equal than in the old world [60], and Gini coefficient is estimated in order of magnitude around 0.2 [148], Turner et al. assumed [142] a strong possibility of conflict with an elite, which showed weakness at this specific time to support the survival of the inhabitants. The elites lost their power, and the social organization disintegrated, even if they had overcome similar threats in the past. As farmers and artisans spread in order to survive like hunter gatherers, from the entropic viewpoint, we note that the entropic index of inequality $\Phi_\mu[x]$ tends toward $-\infty$, indicating the collapsed social structure. In other words, the preservation of the social structure and social cohesion is the prerequisite for the recovery of civilization.

Easter island: The first Polynesian settlers found an island with fertile soil, plenty of food, plenty of building materials and all the conditions for a comfortable living [149]. The redistribution of island resources required a complex social organization of the population [150]. It is alleged that trees were intensively cut to create tools for the construction of the island's monolithic monumental sculptures known as moai (Figure 11b). The construction of these sculptures is presumed to be the result of a competition between different tribes trying to outdo each other in displays of wealth and power.

The big picture is one of the most extreme examples of societal collapse: the entire forest disappeared. As the forest disappeared, life became more and more uncomfortable; the springs disappeared, and wood was no longer available. Humans starved; cannibalism replaced some of the lost food supply [151].



(a)



(b)

Figure 11. (a) Maya: El Castillo, at Chichen Itza [152] (b) Moai facing inland at Ahu Tongariki, restored by Chilean archaeologist Claudio Cristino in the 1990s [153].

The cause of collapse: human acts or the environment? In both well-known cases, we note anthropogenic factors as the cause:

- Maya: the collapse was triggered by droughts (recession), but the reason was the institutional failure from the corruption of the elite.
- Easter island: natural resources were consumed at higher rates than they could be renewed. The reason, which led to a dynamic crisis, was the inability of society to distinguish the real needs and the non-sustainable consumption for the creation of useless symbols of power.

These examples show that, even when the environment is involved as a cause of civilizations' collapse, it could be a trigger but not the cause, with social dynamics and environmental determinism nested in a complex relationship.

4.2. Environmental Determinism in Modern Era

In the modern era, the technological limit and the ability of storage are constantly increasing. Therefore, environmental determinism fails systematically. Typical examples of failures are:

1. The overthrow of the Malthusian trap by (a) the industrial revolution [154]; (b) the formation of the modern economy [84]; and (c) economic development [155].
2. The recovery from the energy crisis caused by whale oil shortages in the 19th century [156–158] with the use of coal [159].
3. The recovery from the health crisis caused by the huge stock of horse manure in cities during the late 19th century (16 kg/d per horse) after the introduction of automobiles [160–162].
4. The nonoccurrence of worldwide famine due to (supposed) overpopulation despite the prediction in the well-known books *The limits to growth* [163] and *The population bomb* [164]. The Green Revolution introduced by Norman Borlaug [165] brought an end to starvation in Asia in the 1960s [166,167], Africa in the 1980s [168] and subsequent support for population growth until today.
5. The spectacular falsification of the predictions of the 1992 AGENDA 21 of the United Nations Conference on Environment and Development, such as this:

We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy [169].

Since then, global poverty has been reduced from 1.71 billion (1992) to 733.48 million (2019) [170]; global average life expectancy increased from 63.1 to 71.4 years [112]; the global share of children who are stunted decreased from 39.3% (1990) to 22.2% (2017) [171]; and the global share of the population over 15 years of age able to read and write increased from 75,3% (1992) to 86,4% (2019) [172] (Figure 12).

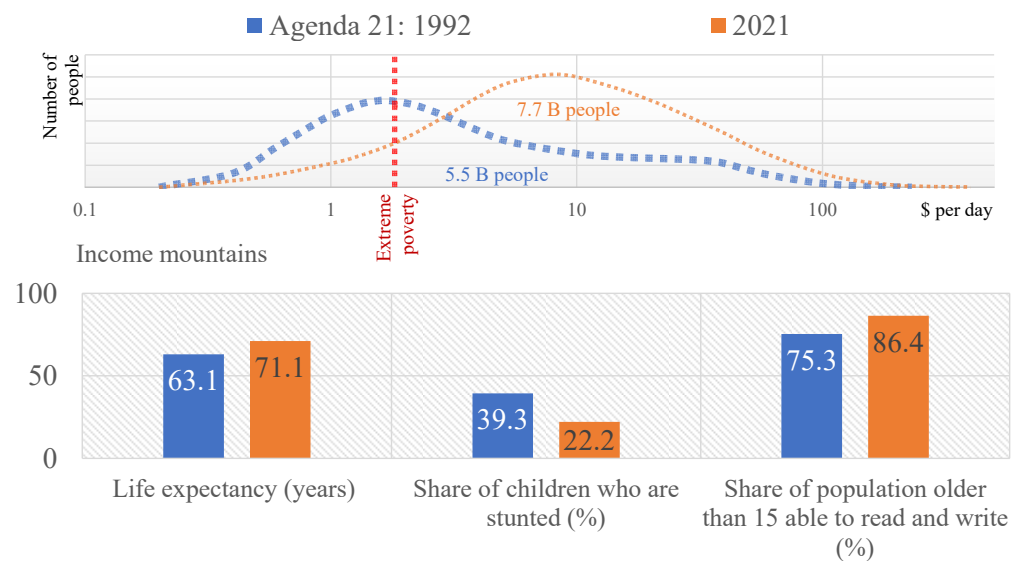


Figure 12. Global data from 1992 (Agenda 21) and 2021. Top: Income mountains [173]; Bottom: Life expectancy (years), share of children who are stunted (%), share of population older than 15 able to read and write (%).

These examples show that Western thought keeps being influenced by environmental determinism despite its continual failures. The question is not whether the environment is related to socio-historical change but how we can deal more objectively with coupled systems that include a large set of variables [174].

In addition, it is tempting to draw parallelisms with the present situation, as in the current conditions: the complexity of the world and the dependence on the digital facilities have reached an impressively high level; global wealth follows the Pareto distribution [83]; high-cost research and technological steps are detached from the real needs (among others, the space trips competition [175]); the type of resource consumption is not sustainable; and we have not solved issues regarding storage capacity (for example, to store energy from the renewable energy resources).

5. Minoan Civilization

The Minoan civilization was an Aegean Bronze Age civilization, which flourished on the island of Crete, the island of Santorini (Akrotiri), other Aegean islands and in the western coastal areas of Asia Minor (modern-day Turkey; Figure 13), from about 3200 to 1100 BC. The historian Will Durant called the Minoans “the first link in the European chain” [176]. This statement is ex post supported by genetic indices, which indicate that the first Neolithic migrants traveled from the Levant into Anatolia and then to eastern Crete, Greece, Sicily and central Europe [177].

The basic stages of the Minoan civilization are:

1. Prepalatial 3250–1900 BC,
2. Protopalatial (Old Palace period) 1900–1750 BC,
3. Neopalatial (New Palace period) 1750–1450 BC,
4. Postpalatial (Knossos, Final Palace period) 1450–1100 BC,
5. Dark Ages 1100–750 BC.

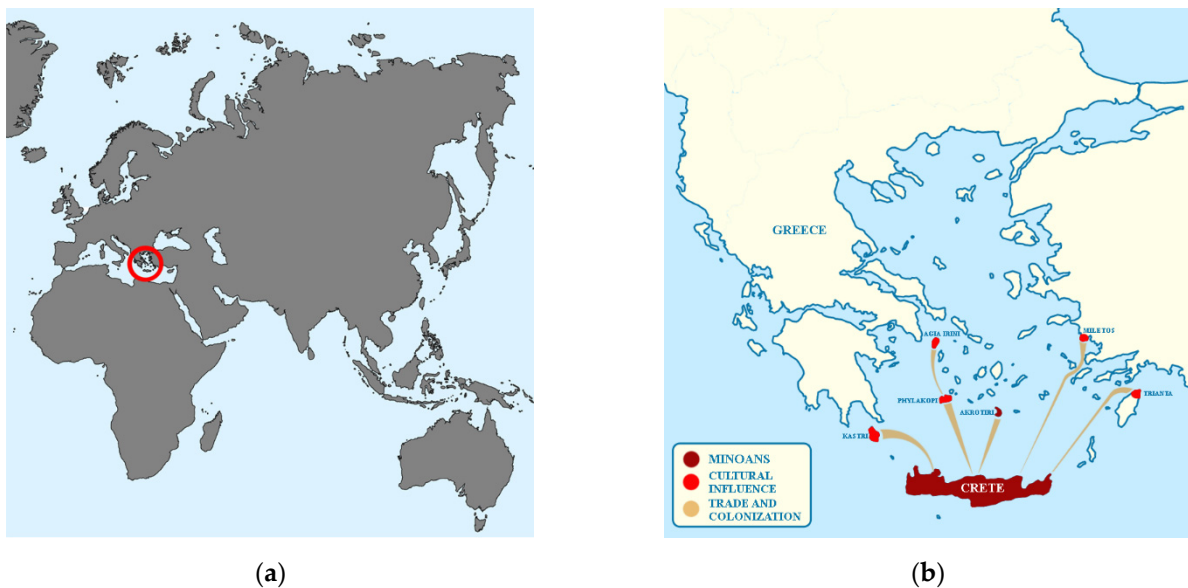


Figure 13. Minoan civilization. (a) Location; (b) Areas of cultural influence (possible colonies), trade and colonization route.

The Minoans represent the first advanced civilization in Europe, leaving behind massive building complexes, tools, stunning artwork, systems of writing and a massive network of trade [178]. They constructed remarkable architectural and hydraulic infrastructure for the management of water resources, such as water supply, fountains, dams, aqueducts, highly sophisticated sewage and drainage systems, toilets, irrigation and drainage of agricultural land [179–182]. Minoans also developed the syllabic scripts known as Linear A and Linear B. Linear B was deciphered by Michael Ventris in 1952 [183,184]. This remarkable civilization was only rediscovered at the beginning of the 20th century through the work of British archaeologist Arthur Evans (1921–1935).

Despite the abundance of objects, images and even inscriptions from the Minoan era, it is still difficult to reconstruct the society's structure. Driessen [185] notes that:

a kinship association in which gender differentiation combined with age and a strong sense of locality shaped Minoan identity.

Adams [186] assumes that there were stratification, elite and commoners, and Kristiansen and Larsson [187] exemplify the current state of thinking in Cretan archaeology in their synoptic study *The Rise of Bronze Age Society*, stating that:

the power of Cretan elites lay in 'institutionalised practices (economic, political and religious) that constituted palatial power.

As there was no mention of wars in the area of Minoans between 3200 to 1100 BC, the Minoan era was named by Evans as *Pax minoica* or Minoan peace [188], a period during which cities did not have walls [189]. Contrary to this consideration, other archeologists believe that the artistic representation of violent hobbies, such as boxing or bull-leaping (Figure 14), show a violent social spirit [190]. This supports the theory that the Minoans had a military aristocracy [191], which, according to Ferguson [192], was the crucial determinant of social formation, together with civil administration and religion (triadic balance). It is important to note that recent archeological evidence supports this theory [193].

Crete has pleasant weather (no need for warm clothes or special protection) [194], no big animals as enemies and a lot of food is produced naturally by trees, small animal hunting and fishing. Therefore, an organized society was not necessary for survival needs, and people could live there easily as hunter gatherers. However, the land's morphology is quite heterogenous with a wide range of altitude and fertile-barren areas. Figures 15 and 16 show the connection between the cultivated areas of modern Crete and the archeological

settlements from the Minoan era (Figure 16), indicating that the limits of fertile areas were connected to Minoan settlements.

Assuming that Minoans could cultivate all areas, as is done in modern times (Figure 15), with traditional methods, Knossos, Phaistos and nearby settlements in the center of Crete could feed more than 110,000 people. In eastern Crete, the palace of Malia could feed more than 2000 people; the area near the palace of Gournia could feed more than 12,000 people; and, assuming that the palace of Zacros exploited the land of Palekastro, it could feed more than 5000 people. In western Crete, Cydonia could feed more than 25,000 people, and the nearby cultivated areas of Aptera could feed about 4000 people [60]. In these cases, we have to consider one more difficulty: transporting the products from the mainland to the cities and palaces and then trading them [195]. As saffron is precious in very small quantity (current price ~EUR 90,000 per kg [196]), it was an ideal product for Minoans to trade (Figure 17a). In addition, we can imagine one important advantage: the sea could be an important food supplier, as is represented in related frescos (Figure 17b).



Figure 14. Minoan fresco in Knossos palace, c. 1600–1450 BC [197].



Figure 15. Limits of fertile areas in 2021, connected with Minoan settlements. Google earth [198] after adaptation.

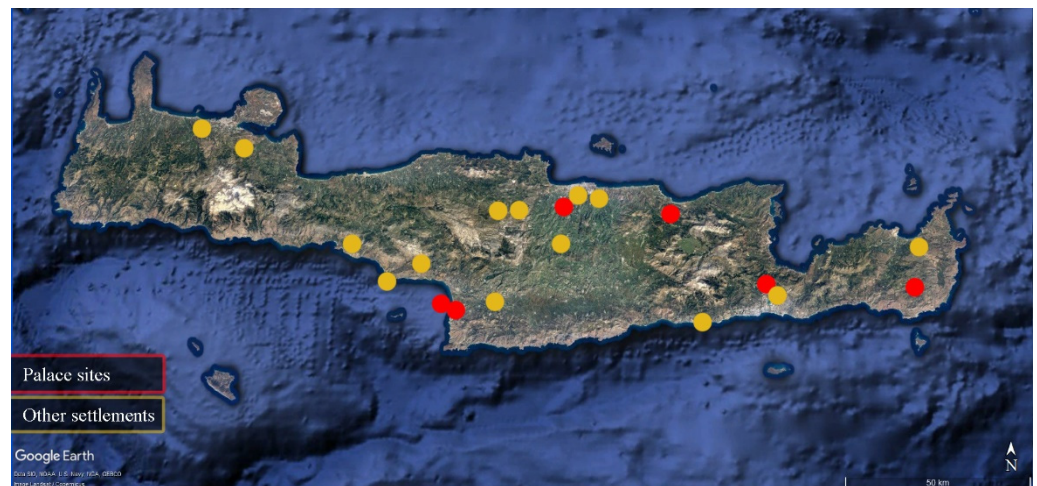


Figure 16. Central Minoan Crete settlements [198].



(a)



(b)

Figure 17. Akrotiri, Santorini c. 1600–1500 BC (a) Saffron gatherers [199] and (b) fishermen [200].

Minoan landscapes were well organized in agricultural and pastoral areas for food production [201]. The high living standards (as evidenced by the hydraulic infrastructure) allowed a dense clustering of humans in cities. Castleden estimates that Knossos had a population of c. 40 000 people in 1500 BC [202] and according to Homer (c. 800 BC), Crete once had 90 cities [203]. Unlike other ancient civilizations, such as in Egypt, Mesopotamia and India, which thrived in areas with high water availability (big rivers), Greek civilizations (and Minoans) thrived in almost the same climate classification but in water-deficient areas, therefore ones susceptible to prolonged droughts, as there was no continuous water supply from big rivers there—and more generally in Greece. Therefore, technological infrastructures were necessary for development in Greek civilizations [204,205].

While there are small rivers and lakes in Crete and the Aegean islands, the Minoan palace and other urban areas were not located close to them. Thus, the remarkable progress in the Minoan Era appears to be inextricably linked with the desire for peaceful coexistence with and adaptation to the natural environment with highly hygienic standards, protection from water-borne diseases and natural hazards (such as floods and droughts) and the comfort of non-primitive living [206–208]. Examining Figures 16 and 18 (rainfall of Crete and Minoan settlements) and the flourishing of western settlements, such as Cydonia in the

pre-palatial period and then Aptera, after the Minoan era, we note that in their prosperity, the Minoans preferred dry places (as did later the Cycladic, Athenians, Spartans, etc.).

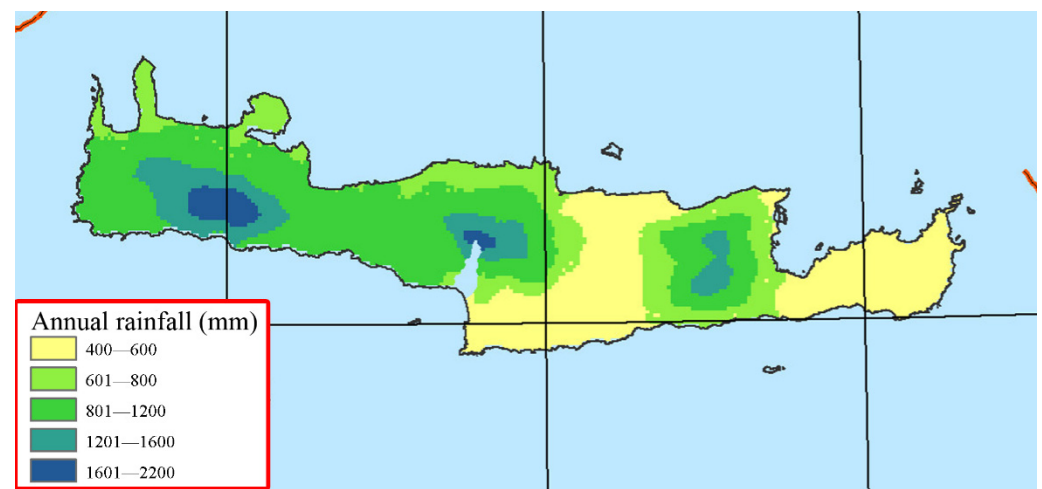


Figure 18. Top: Annual rainfall of Crete (adapted by [209]).

The Minoans exported food, wine, olive oil, herbs, cloth dye obtained from the murex shell and saffron spice [210], as well as other commodities and artifacts. The island's imports consisted of emery, which was imported from Naxos, obsidian, tin, seals and ivory from Anatolia, copper from Cyprus and other places. These traders from various countries were dependent on each other, so that their economies could not only survive but thrive [211].

Studying their way of life, we can see from frescos that the Minoans had great festivals with boats, which indicated societal stratification, as some boats were more decorated than others (Figure 19). We also see that they created highly sophisticated artwork, paintings, sculptures, hydraulic works and ships on which their civilization was based.

These highly sophisticated creations during the Minoan era show that there was a division of labor. It is important to distinguish that life expectancy of people from prehistory until the 1400s was no more than thirty years [212], and one century would mean more than three generations instead of less than one and a half in modern times. Herein, we can also assume that there was a powerful educational system transferring the skills from generation to generation.

Based on the above, we can distinguish the following classes: (a) elite, (b) military class, (c) artists, (d) ship constructors, (e) sailors, (f) craftsmen (houses and hydraulic infrastructures) with high engineering knowledge and (g) farmers and pastorals.

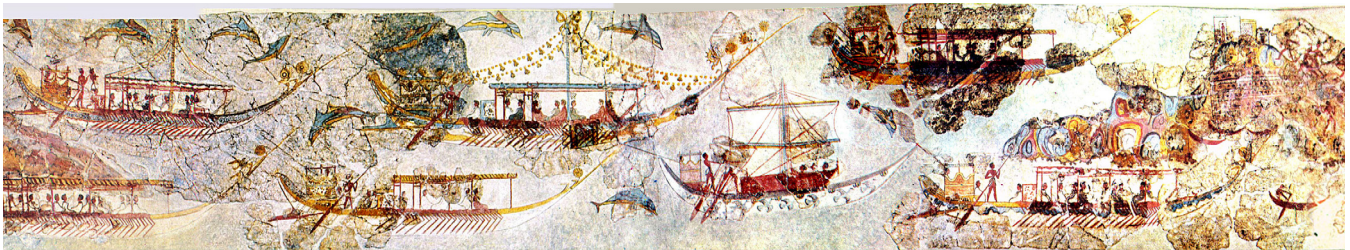
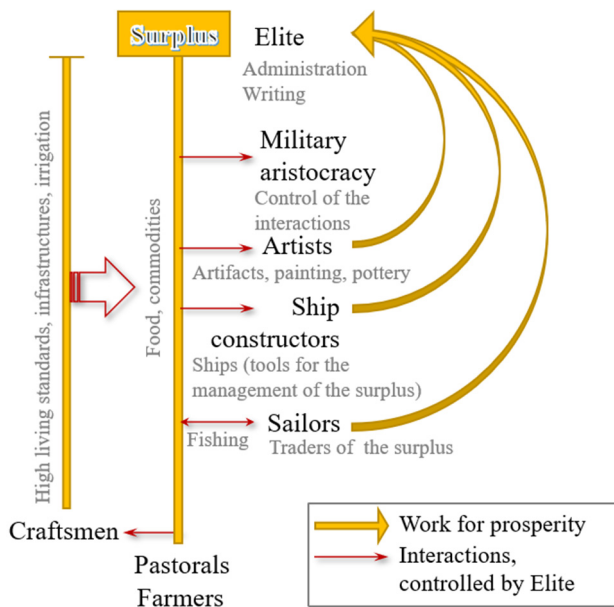


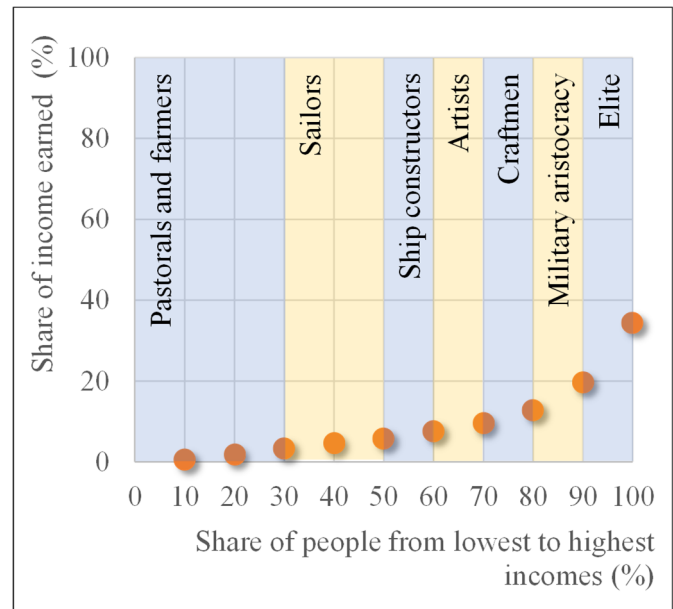
Figure 19. Minoan fresco, ship procession from Akrotiri c. 2000–1500 BC. Sophisticated ships with different decorations suggesting stratification. In the middle, a sailing boat loaded with goods [213].

We may speculate about the role of each one of the classes. The important requirement for production is land. As land required important investment, deforestation, upgrade and irrigation infrastructure, we can assume that the elite invested and managed the

preparation of the land using craftsmen. The craftsmen created high living standards by enhancing the supply of food with irrigation. Farmers and pastorals produced food for all and surplus for trading. Artists created surpluses. Constructors made ships for sailors to trade what were not necessities, also supporting the nutritional needs through fishing (Figure 20a).



(a)



(b)

Figure 20. (a) Creation of wealth and interactions in Minoan society; (b) A hypothetical stratification in Minoan society with Gini coefficient equal to 0.5.

One could assume that there would be a market where people could exchange their goods, but the complexity of the interaction of these classes becomes clear if we imagine a society without money, and the basic goods, which established the prosperity in Minoan era were of high value (infrastructures, ships) and could not be exchanged. Therefore, we can assume that the elite arranged the fees and managed the economy by controlling the interactions and the distribution of wealth. The role of the elite was critical, as the distribution of all the wealth was controlled by them; hence, this could justify a Pareto distribution. However, we impressively see that the distribution is estimated in 1500 BC with a Gini coefficient equal to 0.5 [148], corresponding to exponential distribution, which is the most stable social structure. Even though we do not know the analogies of the Minoan classes, Figure 20b depicts a hypothetical structure of the Minoans' wealth distribution.

6. The Collapse of Minoans

There are many studies attempting to explain the collapse of the Minoan civilization. We could distinguish them by the main cause they propose, i.e., environmental or social.

6.1. Climate Change

Tsonis et al. [214] show that wetter conditions during the middle Holocene period were followed by drier conditions and that around 1450 BC, a long stretch of drier conditions commenced, ending centuries later. The authors presented a synthesis of historical, climatic (associated with an increase in the intensity of the El Niño Southern Oscillation), geologic and model simulations to support the hypothesis that climate change, instigated by an intense El Niño activity starting around 1450 BC and lasting for centuries (resulting from El Niño teleconnections), prolonged the drought conditions in the area, and this contributed to the demise and eventual disappearance of the Minoan civilization. A related study

by Markonis et al. [215] summarized the pressures on the water resources in Crete in connection with climatic variability. Other studies support these research works [216,217].

6.2. Thera Volcano Eruption

The chronological estimates of this eruption differ: 1500–1450 BC [218,219], 1645 BC [220], early 16th century BC [221], 1628 BC [222]. Widely known catastrophic scenarios from the Thera volcano eruption are:

- a. The fallen tephra from Thera on the eastern side of Crete choked off the agricultural production [223], and people lost their creative capacity [224].
- b. A tsunami, likely associated with the eruption, impacted the coastal areas of Crete. It is estimated that the waves from Thera battering northern Crete could have been up to 12 m high in places [225–227]. Such waves would have destroyed boats and coastal villages, even traveling up rivers to flood farmland [228–231]. However, the number of vulnerable Minoan settlements located in the coastal areas was limited.
- c. There is a possibility that the eruption caused significant climatic changes in the eastern Mediterranean region and especially in the Aegean Sea [232–234]. The potential effect of Thera volcano eruption is the possibility of injecting Sulphur dioxide into the stratosphere, as huge amounts of this gas can alter the climate through solar reflection [235,236].

6.3. Fires

From the traces found during the excavations of the various archeological sites, the destruction at this time appears to be the result of a fire. Platon [237], who carried out the excavations at the Minoan places in the area of Hondros, in southeastern Crete, suggested these major disasters were due to fires:

Judging by the strongly cohesive layers and the calcification and burglary that the stones on the wall of the buildings suffered, the destruction of the neo-palatial settlement of Kefalas and its habitation ended after fierce wildfires.

Additionally, the neo-palatial holy sanctuary in Roussos of Hondros was a victim of an extensive wildfire, which is testified by the abundant remains of the *πυρρίκαυστον* layer found at the site [238].

6.4. Pandemic

A final hypothesis is that, according to the archeological findings of skeletons in a chamber tomb excavated in 1975 at Stavros, east of the village Galia and north of Moires, in a recent publication [193], McGeorge assumes that:

Most households must have kept animals for subsistence, so contact with animals at a domestic level would have been inevitable. The risk of contagion within families would have been great, while denser human population clusters would have aided the spread of epidemic diseases like tuberculosis.

6.5. Social Causes

Foreign enemies: The cause of the destruction of the Minoan civilization has been attributed to an invasion by foreign enemies, e.g., the Achaeans from Peloponnese. This view assumes that a campaign, similar to that organized later by the Achaeans against Troy, overthrew the Minoans [239,240].

Unrest: This hypothesis states that the Minoan destruction was caused by internal upheaval, social unrest and conflicts that had been created between the Cretans long before the Achaeans and Mycenaean subjugated them, when the civilization had already deteriorated. In other words, the Cretans began to destroy themselves, allowing external invasion to be easily accomplished, *mutatis mutandis* (i.e., changing what needs to be changed) [241].

7. Evaluating Different Theories of the Collapse of Minoan Civilization

7.1. Climate Change

It appears that the Minoans had responded adequately to the changing climatic conditions during the Middle Bronze Age. At that time, the management of water resources became increasingly important, consistent with a drier climate [242]. Technologies such as gutters, wells and dams, which utilized ceramic mulches to conserve soil moisture, were employed, while the construction of many terraced hillsides was implemented during those periods [243,244]. However, the Minoans always had the option to move to wetter climates (Figure 16), and if there was drought in Crete, they could move to other places (i.e., west) or to existing colonies rather than collapse.

The Minoans were also sailors and traders and could import goods in case of drought, as the Athenians had done a few centuries later.

In any case, climatic and environmental influences cannot be ruled out, even if they are of secondary importance. This is consistent with what Tsonis et al. [214] concluded, i.e.:

While nobody anymore expects any civilization to get extinct because of climate, it is becoming clear that convergent events such as earthquakes and volcanic activity in synergy with climate anomalies may produce significant stress to contemporary populations vis-a-vis their social and economic development.

7.2. Thera Volcano Eruption

The Minoan Civilization in Crete was destroyed much later than the estimated time of eruption—a puzzle that has confounded historians and scientists for decades. A strong possibility is that the ash from Santorini (Thera) overshadowed Crete for a few days but in no way destroyed the Minoan civilization [223]. The final collapse came at least three centuries later, most probably from other endogenous causes. In addition, archaeological and other evidence suggests that after the Thera volcano eruption in the neo-palatial period, a cultural explosion, unprecedented in the history of ancient civilizations, occurred in Crete. This is demonstrated by the advanced hydro technologies developed at that time, as described by Angelakis [245].

In a very interesting recent research paper about how the volcanic climate impacts can act as ultimate and proximate causes of the Chinese dynastic collapse, Gao et al. [42] show a correlation of collapses of Chinese dynasties with volcano eruptions. Although they assume that:

in cases of collapse, that some dynasties persisted for up to a decade post-eruption while others collapsed more rapidly suggests the complexity of the underlying causal contributions and the inadequacy of monocausal or environmentally deterministic interpretations

they show that civilization could be impacted by an eruption but in a short time range (i.e., less than 15 years).

7.3. Fires

There is a possibility that a fire caused deforestation in the island. This could initiate several problems, such as lack of wood for ship construction, which was a key component of the economy. However, no indication has been found or provided on issues such as: location, ignition source, magnitude and cause.

7.4. Pandemic

Norrie discuss the infectious disease epidemics, which could have led to the end of the Bronze Age [246]. As the clustering of people increased in the Minoan civilization, and we are not sure about the hygienic standards for the majority of the society, we could not exclude the possibility of a pandemic, which could break social structure and continuity.

7.5. Social Causes

Foreign enemies: If we accept a devastating attack from the Achaeans, the question remains: since the Achaeans invaded Crete, why did they not stay there to exert their influence, as they had in other places? In addition, there are chronological gaps. Around 1200 BC (100 years before the Minoans' collapse), the Achaean civilization itself ended when the Dorians from the northern Balkan peninsula conquered it. According to the Greek literature, Iliad and Odyssey, the people would rather die defending their homes than escape. In addition, if some Achaeans escaped with ships from a Dorian attack and immigrated to Crete, displacing the Minoans, we should find their footprint. Until now, archeological evidence does not confirm this theory.

Unrest: The Minoans learned to live with the comforts of non-primitive living. In order to do this, they had to create infrastructure and ships that could not be exchanged in local markets and colonies. Infrastructure and large-scale transportation infrastructure (such as ships) need capital. In the case of the Minoans, we have to imagine a society without money; therefore, we have to assume that all the interaction, which money represented, should have been engaged in by an elite based on an organized bureaucracy [247]. Therefore, the elite would be absolutely necessary in the society's function, and an unrest seems unlikely.

8. Discussion

The Minoans did not thrive in an isolated environment. Even if their technology was limited and the ability of storage was small, they could find resources in other places to support their civilization. Their trading skills and their colonies indicate that they had honed their abilities to find new resources, as they were flexible "predators".

The Gini coefficient in Knossos c. 1500 BC, is estimated at about 0.5 [148]. This value corresponds to the exponential stratification, which is referred to an entropic index of inequality $\Phi_{\mu}[\underline{x}]$ equal to 1 [83] and shows a stable social structure (maximized entropy) in which a recession phase would have minimum effect.

In this era, the Minoans managed to overcome the recession phases caused by environmental causes (Thera volcano eruption and climate changes). If we consider that, in antiquity, life expectancy was no more than 30 years [212], then from the stable social structure (1500 BC) to the collapse phase (1100 BC) there were at least ten generations, which could transform the elite's social perceptions into greediness, creating unstable social conditions.

In addition, the Minoans had an economy organized with complex interactions (in place of money) controlled by the elite. This economy was based on large-scale projects (infrastructure, ships) focused on high living standards, the creation of a surplus and, overall, producing a positive-sum economy.

If we consider the social utility of the Minoans' different classes, we see that we could not leave aside one class and imagine that their civilization could live in prosperity. This complex social structure (Figure 20) thrived for centuries, increasing its entropy (uncertainty) and complexity. Therefore, we could assume that an accident in which the Minoans could lose the ability to manage their complex structure (e.g., a plague or a sudden loss of important members of the society) would be more likely and catastrophic, as it would reduce the efficiency of the society. The average income would be decreased, the social structure would be unstable, and their civilization would acquire a dynamic of collapse.

9. Conclusions

Human civilizations have survived through natural disasters, climate changes and in hostile environments. We see from different examples that when there was advanced social organization, the society could overcome environmental issues, as the Minoans did, in spite of a volcano eruption or climatic changes around 1500 BC. We have also seen several studies, which failed to predict or model society structures (past or present) based

on environmental criteria alone. In addition, it is an undeniable fact that when social organization collapses, societies cannot survive.

In general, we note that environmental determinism is surprised, impressed and fascinated by the natural phenomena and connects them with societies without considering their dynamics. However, we see that the creative capacities (technology, trading, storage), type of consumption (sustainable, non-sustainable), development (growth–recession), social dynamics and complexity of a civilization have an important role in sustainability. The Greek archeologist Christos Doumas notes [248]:

*τα φυσικά φαινόμενα δεν τερματίζουν πολιτισμούς εφόσον επιβιώνουν οι άνθρωποι
(natural phenomena do not demise civilizations as long as people survive).*

Therefore, it is important to understand how the evolutionary trajectory of early civilizations was disrupted. Clearly, the expected recession phases, which are described by HK dynamics, suggest a repeatability element in which ancient civilizations were vulnerable. However, even ancient civilizations, such as Mayan and Minoan, were able to withstand many of these phases, probably with good social organization and the management of a wise elite.

The case of the Minoans illustrates that the key to a civilization's ability to thrive is its focus on large-scale infrastructure and technology that improves the living conditions. This presupposes but also enhances the society's organization. Following this simple rule, societies take the advantages of economies of scale to prey effectively within the water–energy–food nexus necessary for survival and prosperity. In order to do this, organization, division of labor (necessarily leading to social stratification) and growth (necessarily leading to complexity) are necessary. In light of this, we therefore deem social dynamics as important, if not the most important, in comparison with environmental determinism considerations.

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