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*Commentary*

# Strong Fuzzy EHLFS: A General Conceptual Framework to Address Past Records of Environmental, Ecological and Cultural Change

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**Abstract:** Although the interpretation of Quaternary records of interrelated environmental–ecological–human processes is necessarily complex, it is often addressed using too-simple deterministic approaches. This paper suggests a holistic framework called EHLFS (Environmental–Human–Landscape Feedbacks and Synergies) to tackle Quaternary complexity. The EHLFS scheme is a multiple-working-hypotheses framework, able to account for the particular nature of Quaternary research, and is used in combination with the strong inference method of hypothesis testing. The resulting system is called the strong fuzzy EHLFS approach. This approach is explained in some detail and compared with the more extended simplistic determinisms—namely the environmental determinism and the human determinism—as well as with dual determinisms or deterministic approaches based on two contrasting and apparently contradictory and excluding hypotheses or theories. The application of the strong EHLFS methodology is illustrated using the Late Holocene ecological and cultural history of Easter Island since its initial human settlement, a topic that has traditionally been addressed using simplistic and dual deterministic approaches. The strong fuzzy EHLFS approach seems to be a robust framework to address past complex issues where environment, humans and landscape interact, as well as an open system able to encompass new challenging evidence and thorough changes in fundamental research questions.

**Keywords:** Quaternary complexity; simplistic determinism; dual determinism; multiple working hypotheses; falsification; strong inference; EHLFS

## 1. Introduction

Quaternary records of environmental, ecological and cultural change are expressions of complex patterns and processes involving not only the corresponding physicochemical, biological and human elements but also the dynamic interactions among them at multiple spatiotemporal scales [1]. Therefore, interpreting such records requires complex thinking. However, there is a tendency to simplify until the point of attributing a single phenomenon to a single cause, a practice that has been called simplistic one-to-one determinism [2] and has generated long and intense debates and controversies. Examples are environmental determinism or human determinism, where environmental or societal changes, respectively, are considered to be the main causes of ecological and cultural change. This type of determinism is especially manifest in the interpretation of apparent and often abrupt events as for example deforestation, desertification or societal collapses, among others [3]. It is also frequent that the competition between two contrasting views of the same phenomenon can persist for decades in the form of classical controversies. This is also a form of determinism called here dual determinism.

Simplistic and dual determinism can arise from different sources. Sometimes, they are the result of differences in the particular background and methodology of the diverse research specialties that participate in Quaternary research. This may lead to the segregation, and eventually the confrontation, of these research disciplines, which is contrary to the integrative nature of Quaternary study [1]. Narrow-focused determinism can also emanate from the resistance to changing one's hypotheses and theories, even when apparently contradictory evidence comes to light. Current research environment also favors the proliferation of simplistic approaches. Publishing in high-impact journals, based on citation records, is increasingly needed for a successful scientific career. Some of these journals encourage short, simple and challenging proposals leading to controversy, rather than deep and thorough evaluations of the existing evidence. In addition, nonscientific marketing techniques are commonly used to increase the impact of papers and their authors, which has become a favorable criterion for academic institutions to recruit researchers, grant personal promotions and fund projects. Such a system promotes partiality and simplicity [4].

More comprehensive approaches are needed to overcome unwarranted simplistic and dual determinism, in order to transmit a sound knowledge legacy to the future generations. This essay suggests a holistic approach to Quaternary complexity whose core is a general conceptual framework called EHLFS (Environmental–Human–Landscape Feedbacks and Synergies), able to accommodate multiple lines of evidence that, in a deterministic environment, might seem contradictory. The strong fuzzy EHFLS approach is based on the EHLFS framework plus the methods of multiple working hypotheses [5] and strong inference [6], and considers the particular nature of the hypothesis testing approach in Quaternary research, called here the fuzzy approach, which is common to many other earth sciences and different from experimental sciences. The paper begins with a brief account of the methods of multiple working hypotheses and strong inference. Then, the distinct features of the fuzzy approach are discussed. The third part presents the EHLFS framework itself and analyzes the more common determinisms under this scheme. Finally, a case study is presented to illustrate how a classical controversial topic traditionally based on both simplistic and dual determinism can be addressed using the strong fuzzy EHLFS approach yielding a more complete view able to account for most available evidence.

## 2. Multiple Working Hypotheses, Falsification and Strong Inference

The multiple working hypothesis framework was developed by the North American geologist Thomas Chamberlin (Figure 1), the founder of the *Journal of Geology*, almost 130 years ago [5]. According to this author, when we develop a theory that seems satisfactory to explain a given phenomenon, there is the danger of remaining too attached to it with a sort of parental affection that may lead us to unconsciously select and magnify the supporting evidence, neglecting the empirical data that could contradict our intellectual child. Sooner or later, this favorite theory becomes a ruling theory, that is, a theory that controls and directs further research, no matter if it is built on sound evidence or is a premature explanation based on insufficient empirical data. Eventually, a ruling theory may turn into a paradigm around which research is organized, and a yes-and-no debate between defenders and detractors establishes, thus blocking eventual progress towards alternative explanations [5]. If, eventually, an alternative theory emerges, the controversy may turn into a dual debate between the supporters of either one or the other ruling theory, which is still a deterministic research framework that ignores other possibilities. In either case, a debate exists that may lead to subjective personal or partisan discussions where the objective is to be right and the opponents wrong, rather than to find the better explanation for the observed phenomenon [7]. Such an endless loop can only be broken by a change of mindset towards a more open-minded framework, as for example the multiple working hypotheses, where any possible explanation is explored and every testable hypothesis is developed. This approach promotes thoroughness, suggests lines of inquiry that might otherwise be overlooked and develops the habit of parallel and complex thought [5].

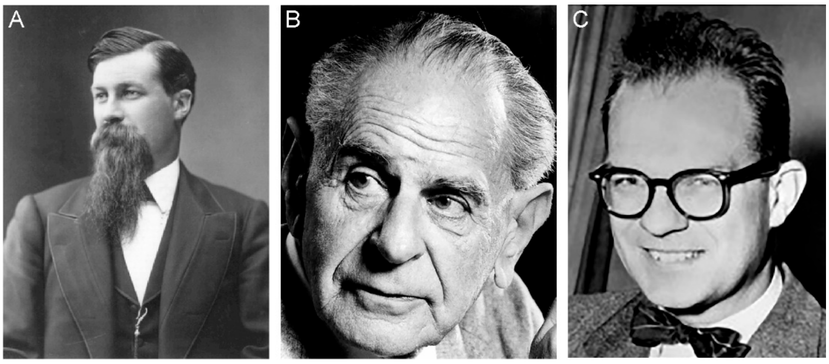


**Figure 1.** The three researchers who developed the ideas that constitute the theoretical foundations of the strong fuzzy EHLFS (Environmental–Human–Landscape Feedbacks and Synergies) approach. (**A**) Thomas Chrowder Chamberlin (1843–1928) in the 1870s. Source: University of Wisconsin-Madison Archives. (**B**) Karl Raimund Popper (1902–1994) in the 1980s. Source: Library of the London School of Economics and Political Science. (**C**) John Rader Platt (1918–1992). Source: Google Arts & Culture. Photographs with license Wikimedia Commons.

The multiple hypotheses framework is the ideal arena for empirical falsification, a procedure introduced by the Austrian–British philosopher of science Karl Popper (Figure 1). This author argued that a scientific hypothesis cannot be definitively proved because, sooner or later, an alternative hypothesis may appear that is as good or better at explaining the observed phenomenon. In addition, new empirical evidence may eventually appear that challenges the current paradigm and requires its reconsideration. According to Popper [8], the only possible procedure is to prove that a given hypothesis is false then move to another possibility to do the same and so on. The hypotheses that survive this falsification process are the better suited to explain the empirical observations. Therefore, science advances only by disproof. In this framework, the multiple working hypotheses approach provides the raw material needed for the falsification process. The method of strong inference, developed by the North American biophysicist John Platt (Figure 1), is in fact an updating of the inductive method of Francis Bacon (1561–1626), the father of empiricism and the inductive reasoning as the foundations of modern science. Strong inference demands to look constantly for alternative hypotheses and devise which experiments or observations are needed to exclude them. This procedure should be repeated with sub-hypotheses or sequential hypotheses, in order to refine the possibilities that remain [6]. Platt urges the researchers to permanently ask themselves what kind of experiment or observation would be needed to disprove their own hypotheses and to proceed accordingly. Defined in this way, strong inference includes both the multiple working hypotheses scenario and the Popperian falsification.

## 3. The Fuzzy Approach

Although past records have been considered a kind of natural experiment, their interpretation exhibits significant differences with respect to experimental sciences. In Quaternary research, evidence is not experimental, in the classical sense, but observational. Hypothesis testing proceeds by seeking empirical support or disproof in past records, which have been considered as natural laboratories where one can look for empirical confirmation or refutation of the existing hypotheses. The main difference is that classical experiments are planned and controlled activities aimed at testing one or few well-defined hypotheses at the same time, whereas the evidence present in past records is manifold and largely unpredictable. Rather than a methodological constraint, this could be viewed as a favorable scenario for complex thinking, as researchers are bound to envisage as many possibilities as possible before the evidence comes to light. In Quaternary study, the initial hypotheses define the location, the type and the age of past records to be obtained, as well as the proxies to be analyzed. Researchers have the option of choosing a particular set of variables aimed at addressing particular questions or developing a wide multidisciplinary analysis to acquire as much information as possible on the condition and functioning of the past natural system under study. The first option is more similar to the classical experimental approach and the ruling-theory approach, which is preferred by funding agencies that adhere to the ruling-theory approach (actually, most of them), because it is more target-oriented and requires smaller budgets. The main challenge is the uncertainty of past records, which could lead to the failure of the "experiment" if the desired evidence is not available. Another drawback is that, even in the case of a successful output, there are many variables that have not been taken into account and could have a role in the explanation of the process under study. The wide multidisciplinary approach, although it requires more investment, is able to produce better explanations of the system as a whole and also to make more discoveries. Indeed, new findings usually come from unexpected results, which are much easier to be obtained using a wide research perspective than a narrow-focused research plan based on ruling theories.

Many Quaternary researchers (the author included) do not confess that they actually lack definite expectations from novel records and that they go to the field simply to obtain samples and see what happens. Research interests do exist but they are fuzzy and there is not a particular a priori hypothesis or ruling theory to be tested. This could be considered blasphemy, especially under the rules of the current research system, which is aimed at solving short-term specific problems of social and/or economic interest. Under such rules, Darwin would hardly have developed the theory of biological evolution, as even he himself was not aware of such an objective. Darwin's discoveries came from candid observation of natural phenomena. Darwin would hardly have been funded by present-day agencies that require a set of conditions that he was unable to provide, such as a definite short-term objective aimed at solving a specific problem, a definite research plan—besides voyaging around the world and taking notes in his field notebook—and an explicit publication program based on quantitative impact estimations, rather than on several voluminous books [9]. Some funding agencies, as for example the European Research Council, look for geniuses like Darwin and offer high budgets to individual scientists with amazing quantitative research records. But even in this case, the objectives should be clear, the research program well defined and the publication expectations exceptional, in quantitative terms. These are high-risk programs and the funded researchers are allowed to fail, but they are asked to anticipate the potential challenges of their proposal that might lead to failure. The next step might be to anticipate the results of the research, for which no funding is needed. This is still the same ruling-theory framework and it is very difficult to be successfully applied in earth sciences, where a fuzzy research framework seems more powerful and is actually practiced by many scientists, whether or not they are aware of it.

Under a fuzzy approach, there is a broadly defined research objective including a number of known and unknown potential targets of interest, for which multiple hypotheses can be erected. The known targets emerge from previous studies and the own background and interests of the researchers and research teams. These targets are not necessarily immutable, as they can be modified or abandoned, and their priorities changed, in the course of research. The unknown targets emerge during the development of the study and, due to the nature of the Quaternary records, they cannot be anticipated. Each target has its own body of multiple hypotheses, which may be complementary or may be shared with the other targets. In this framework, multiple hypothesis testing is a permanent activity and guides the development of the project. Eventually, the whole research objective may be questioned and changed while the research progresses. Many Quaternary scientists, and others, are familiar with the fuzzy framework but they are also aware that a proposal like this would be considered of low priority by a funding agency. The usual strategy is to follow a ruling-theory approach to prepare the proposal and try to develop fuzzy research once approved.

The fuzzy approach, however, does not necessarily involve Popperian falsification and strong inference, as hypothesis testing may also proceed by seeking for empirical evidence to support one or another potential explanation, rather than falsification. To incorporate strong inference (in which falsification is already included, see above) to this scheme, hypothesis confirmation should progress by refutation of all the existing alternative hypotheses. But such refutation should be explicit. Finding support for a given hypothesis is not enough to falsify all the others, as a number of them cannot be excluding but complementary. It is not unusual to present two hypotheses as contradictory and excluding, when actually they are not. This is called here the fake dual determinism. This occurs when hypotheses are not general enough and the evidence is selected to defend either one or another. A more general hypothesis may be erected that is compatible with all the body of available evidence. The combination of the fuzzy approach and strong inference approaches is called here the strong fuzzy approach, which is a more natural framework for Quaternary research.

## 4. The EHLFS System

The EHLFS framework is a generalization of a former approach called CLAFS (Climate–Landscape–Anthropogenic Feedbacks and Synergies), which was developed for a particular case study [10]. It is expected that EHLFS will be of more general application, no matter the geographical context and the particular environmental and ecological features of the region under study.

### *4.1. Rationale*

EHLFS could be viewed as a functional system formed by three basic components or subsystems, namely the environment (E), the humans (H) and the landscape (L), as well as their corresponding interactions, expressed in all the potential feedbacks (F) and synergies (S) within and among them (Figure 2). The three basic subsystems (E, H and L) are composed of many elements, some of which are particularly relevant to define and characterize the interactions among them. Major environmental elements are climate change, geological patterns or environmental hazards (volcanism, earthquakes), as well as all the associated astronomical, atmospheric, oceanic and lithospheric processes. The human component is represented mainly by activities related to land use, occupation and transformation, and the related processes, notably the exploitation of natural resources, demographic changes, technological improvements, migratory patterns, war and other societal conflicts, communication networks, and so on. Rather than a merely descriptive unit, the landscape is treated here as an ecological component, that is, a functional entity formed by the assembly of the different ecosystems that live together in a given region and interact with each other. In terrestrial ecosystems, vegetation is a major landscape feature and its dynamics over time and space is commonly used as a proxy for general ecological dynamics.

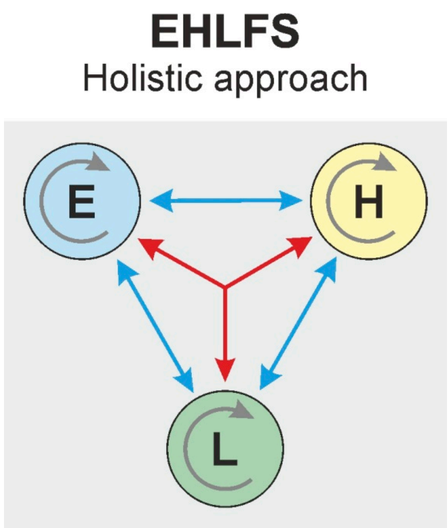


**Figure 2.** Schematic view of the EHLFS holistic approach. E: Environment, L: Landscape, H: Humans. Feedbacks are represented by blue arrows and synergies in red arrows. Grey arrows represent internal feedbacks.

Internal feedbacks within E, H and L influence the output of each of these subsystems and, therefore, the nature of the interactions among them (external interactions). A relevant feature of internal and external feedbacks is the occurrence of amplification mechanisms that can lead to unexpected outputs as a result of nonlinear responses [11–14]. For example, although Pleistocene glacial cyclicity has followed the pace of astronomical cycles of insolation, the intensity of these cycles seems not enough to have fostered the temperature changes needed for glacial–interglacial alternation. Changes in the atmospheric composition, the global oceanic circulation and/or the albedo have been suggested as the main amplification mechanisms. Nonlinear responses can also occur among the EHLFS subsystems. For example, a shift to more arid climates (E) can cause changes from forested to more open landscapes (L), which may increase evaporation and enhance local climatic aridification thus amplifying the initial climatic signal and triggering a positive feedback that can eventually lead to desertification. In this case, climate is the initial forcing factor but landscape features also influence climatic trends at local and regional scales. Similar amplification processes can occur between H and L in the case of human deforestation by fire, which enhances vegetation flammability and exacerbates fire proliferation. The concurrence of climatic dryness and human deforestation is an example of synergy, in this case between E and H acting on L, whose devastating potential is notably enhanced by the coupling of multiple feedbacks among the three subsystems. In this case, landscape changes (L) affect both climate (E) and humans (H), as deforestation patterns may influence, for example, human settlement, demography and land use.

The influence of human activities on environmental and landscape features has increased throughout the Quaternary. At the beginning, with the *Australopithecus* and the first *Homo* species, the influence was absent or negligible. In such pristine condition, the H element was virtually absent from the system, which was composed only by the E and L subsystems and their internal and external feedbacks. Alternatively, it could be considered that, in such primitive conditions, H would be part of E. Synergies were still absent and the system was an ELF (Figure 3). With time, human influence increased and the system became complete, with all the elements and their respective internal and external feedbacks and synergies. The full establishment of the EHFLS system, at a global level, can be traced back to the Late Glacial, with the worldwide human spread after the colonization of the American continent. Human influence became more decisive in the Middle Holocene, after the worldwide establishment and expansion of the agriculture and the incoming of sedentary societies. Since then, the Earth has experienced a profound anthropogenic transformation, mainly on the L subsystem. During the last centuries, the Industrial Revolution has resulted in a new state in which humans have upgraded the impact until the point of affecting global patterns and processes, including the functioning of the Earth System [15], although some authors consider that this would have happened before, during the Middle Holocene [16]. At present, our impact on the E and L subsystems has attained unprecedented levels, especially in the E component, as our influence on climate has transcended the local and regional extent to become global, as manifested in the ongoing global warming, as a consequence of the anthropogenic increase in the atmospheric concentration of greenhouse gases.

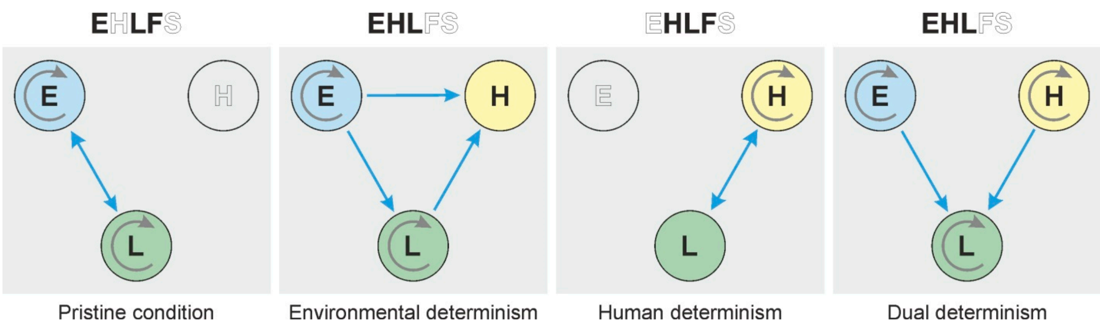


**Figure 3.** The pristine condition and the types of determinism discussed in this paper, under the general EHLFS framework. See Figure 2 for details.

By construction, the EHLFS approach is suitable for analysis of environmental, ecological and cultural change under a multiple-working-hypotheses perspective, as it considers all the possible explanations for an observed phenomenon. If the strong fuzzy approach is added, we obtain the strong fuzzy EHLFS framework, which includes Popperian falsification and strong inference, in the sense expressed above. The strong fuzzy EHLFS framework guarantees that hypotheses and theories are general enough to account for most of the available evidence, thus minimizing the danger of too narrow-focused proposals and the use of selected evidence to support them, as may occur in simplistic and dual determinisms.

*4.2. EHLFS and Determinism*

Simple and dual deterministic approaches may be viewed as a priori simplifications of the EHLFS system. For example, the so-called environmental determinism considers that environmental changes are the main drivers of ecological turnover, landscape degradation and/or cultural disruption. This model has been used to explain the collapse of past societies and civilizations—as for example the Akkadian empire in the Near East or the Classic Maya empire in Mesoamerica—through the Holocene due to the occurrence of unexpected climatic events, notably droughts [17]. Environmental determinism has been criticized arguing that it does not consider the complexity of human societies and their relationships with the ecological systems and the environment. However, environmental determinism survives because most critiques are based on logical reasoning and the evidence needed to falsify it is still unavailable. This is a typical case of determinism due to different disciplinary approaches, as the dominance of environmental changes on human affairs is usually defended by palaeoclimatologists, whereas criticism comes mainly from social sciences. Within the framework of this study, the environmental determinism may be considered an EHLS system, where the environment (E) acts directly or indirectly—via landscape (L) degradation—on human societies (H), with no feedbacks between humans and the other subsystems (Figure 3). The incorporation of sound evidence from the human subsystem is needed to add these feedbacks, as well as the internal H feedbacks, and to properly analyze the problem from a more general perspective.

Human determinism attributes ecological and cultural changes to anthropogenic causes and neglects the potential effects of eventual environmental shifts. A classic example is the human settlement of remote oceanic islands and the ensuing landscape and societal changes. For example, in the remote archipelagos of the Pacific Ocean, Mid-to-Late Holocene human colonization resulted in catastrophic landscape shifts and biodiversity declines mainly due to deforestation, over-hunting and the introduction of alien predators and competitors [18]. Anthropogenic transformations have been so intense and extended that the potential effects of environmental changes on landscape seem to have been negligible. In this case, human action is clearly visible in the palaeoecological record and cannot be ignored, but a potential role for environmental changes such as the Medieval Climatic Anomaly (MCA) or the Little Ice Age (LIA), among others, has not yet been falsified. Some chronological coincidences have been proposed to exist between those Late Holocene climatic shifts and the navigating capacity of humans or their ability to exploit natural resources [19]. A number of researchers believe that climatic forcing has been negligible but this view has not yet been properly tested. Others contend that climate would have had a role but the magnitude of anthropogenic impact obscures the palaeoecological record of such influence. In the present state of knowledge, human determinism seems to be the winning option, by far. In this case, the system is an HLF, with only two subsystems (H and L) and their corresponding feedbacks but no synergies. Internal landscape feedbacks are negligible as landscape patterns and processes are considered to be fully controlled by human activities.

Dual controversies are also frequent in Quaternary study. A typical case is the origin of the high tropical diversity, which has been attributed to either pre-Quaternary tectonic and palaeogeographic changes by some authors, or to Quaternary climatic shifts by others [20]. The debate between the potential role of either environmental shifts or human activities on the landscape and its ecosystems is also a hot topic. For example, some authors contend that the Mediterranean biome has been originated primarily by the action of a progressive aridification process starting in the Middle Holocene, while others believe that human activities, notably fire, have been more decisive [21,22]. An example that is now under hot discussion is the natural or anthropogenic nature of the hyperdiverse Amazonian rainforests. Such forests have been traditionally considered among the most pristine ecosystems on Earth but recent studies have suggested that pre-Columbian indigenous people were more numerous than previously thought and are largely responsible for the present composition of Amazonian forests [23]. This view has been challenged by those who consider the evidence insufficient to support such a proposal and who rely on natural drivers to explain the current Amazonian biodiversity patterns [24]. Selective evidence is used to support either proposal but, to date, neither of them has been able to be falsified. As in the case of environmental determinism, this type of controversy falls within an EHL framework, but this time the focus is on landscape (L), rather than on humans (H), and the feedbacks and synergies between Environment (E) and humans are rarely considered.

In the above cases and examples, and many others, finding support for a given hypothesis is usually considered enough for automatic refutation of the contrasting view. However, in the strong fuzzy approach, falsification should be explicit and should include all the alternative hypotheses possible. In addition, downgrading the EHLFS system to more simple EHLS, HLF or EHL versions reduces the interpretive potential and may bias the output towards subjective interests. The use of the full EHLFS framework provides a more general scope to account for the whole body of available evidence. If, eventually, after the use of a full strong fuzzy EHLFS approach, a more simple ELF, EHL or HLF framework emerges, this would be considered a sound output favoring determinism (intense and/or large-scale natural hazards would be an example). But if a given simplification is imposed from the beginning as an axiomatic premise, the output can only be subjective.

## 5. An Emblematic Case Study

Easter Island (Rapa Nui, in indigenous language) has been the arena of vivid debates under the frameworks of ruling theories and dual controversies, and the cradle where the CLAFS approach—the precursor of the strong fuzzy EHLFS approach—was born. In the local language, the island is called Rapa Nui and the indigenous civilization and its descendants are known as the Rapanui people or the Rapanuis. This volcanic island is located in the southeastern Pacific Ocean, in an intermediate position between Polynesia and South America, and is famous for its megalithic statues, the *moais*, built by an ancestral civilization (Figure 4). These statues were the subject of the ancient Rapanui cult and were carved on the soft volcanic tufa of the crater that forms the Lake Raraku catchment using tools made from harder basaltic rocks obtained from other craters [25,26]. The ancient Rapanui civilization did not know metals. Lake Raraku is one of the three only permanent freshwater sources of the island, where no superficial water currents exist due to the high porosity of its volcanic rocks [27]. Freshwater availability is, and has been historically, a strong limiting factor on Easter Island. The other permanent freshwater bodies are Lake Kao and the Aroi bog (Figure 4), also located inside volcanic craters. A number of enigmas surround Easter Island's ecological and cultural history. Here, two of them will be used to illustrate the use of the strong fuzzy EHLFS approach and its variants. The first is the timing of human settlement and the origin of the first colonizers, who are proposed to have been either Polynesians or Amerindians. The second is the end of the *moai* culture and its replacement by the so-called Birdman culture, which represented a cultural revolution, involving radical shifts in lifestyle, sociopolitical organization and religious performance, as well as profound geographical rearrangement [28].

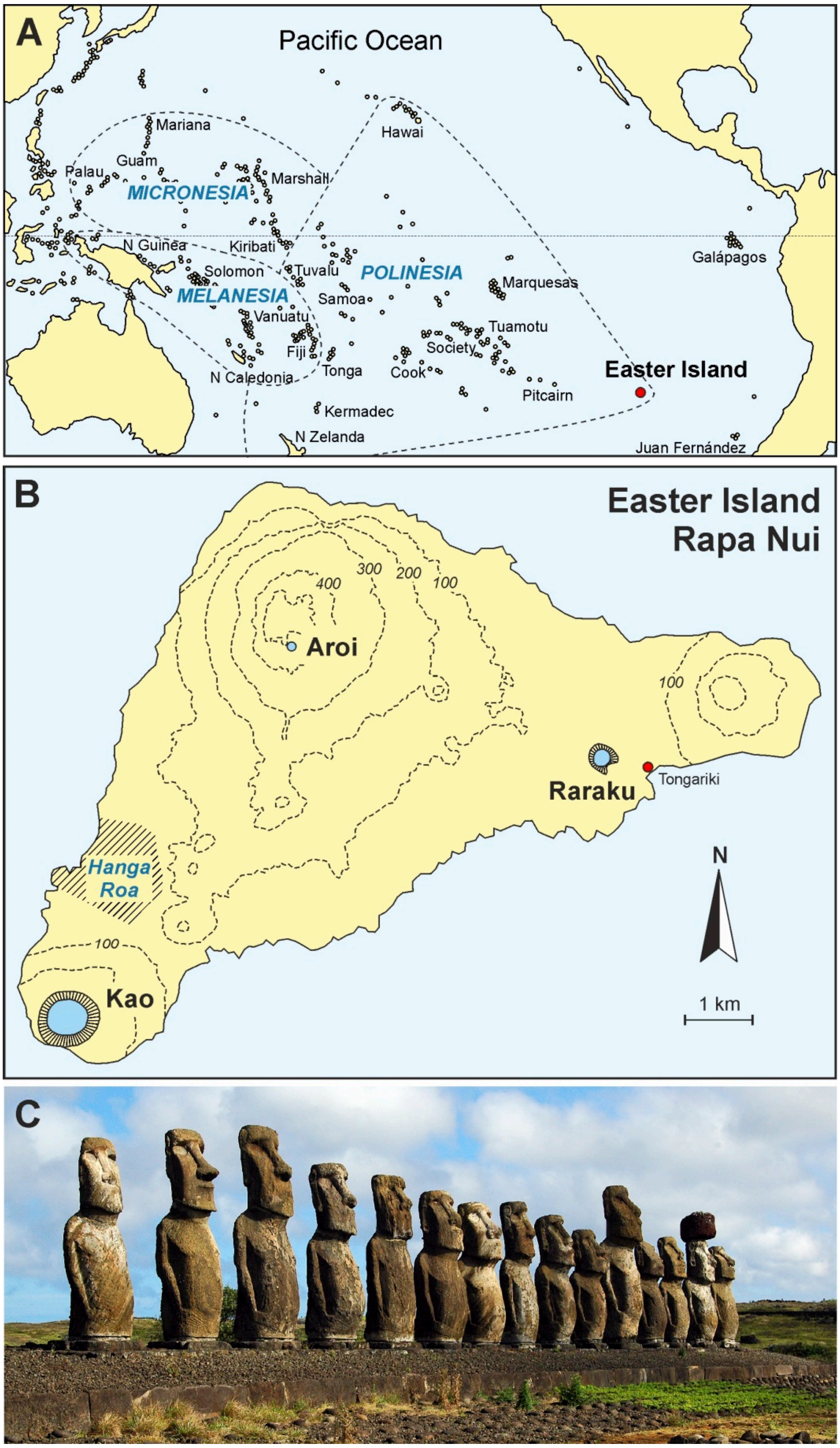


**Figure 4.** Location sketch-maps and *moais*. (**A**) Map of the Pacific Ocean and its main islands and archipelagos. Easter Island is highlighted by a red dot. (**B**) Map of Easter Island, showing the location of the freshwater bodies discussed in the text. Ahu Tongariki (see (**C**)) is represented by a red dot. (**C**) *Moais* of Ahu Tongariki, close to Lake Raraku, see B for location (Photo: N. Cañellas).

### *5.1. The First Settlers: Amerindians or Polynesians?*

According to the Rapanui oral tradition, this civilization arrived on the island from Polynesia, possibly from the Marquesas Islands (Figure 4). But the Norwegian explorer Thor Heyerdahl (1914–2002) imagined that the first settlers could have been Amerindians and decided to prove it by travelling from South America through the Pacific Ocean in a raft, only with the aid of the wind and the ocean currents. This was the famous *Kon-Tiki* expedition (1947), which arrived at the Tuamotu Islands after about 100 days of navigation. Heyerdahl considered that the ancient Amerindians would have colonized Easter Island with the aid of their rudimentary navigation technology and tried to support this view with the available archaeological, ethnographic, linguistic and historical evidence [29]. However, the same evidence was used later to support a unique Polynesian colonization, which has been the paradigm since then [30]. The arrival date is still under discussion and ranges from approximately CE 800 to CE 1200 [31]. Today, archaeologists, ethnographers and historians agree that the current Rapanui culture is clearly of Polynesian origin but this is not incompatible with the ideas of Heyerdahl, who believed that the original Amerindian settlers were exterminated by the Polynesian invaders who arrived later. Such an idea was considered too speculative and was not taken seriously by the scientific community.

### *5.2. The Cultural Collapse: Ecocide or Genocide?*

The first palaeoecological reconstructions, published in the 1980s, suggested that the island would have been covered by extensive palm forests that totally disappeared by sometime between CE 800 and CE 1400, and were replaced by the herbaceous meadows that currently cover the island [32]. Such apparently abrupt and thorough deforestation was interpreted in terms of overexploitation of natural resources by the ancient Rapanui civilization that built the *moais*, leading to its own societal collapse [30]. This is known as the ecocidal theory and has ruled Easter Island research for decades. Such a ruling theory was used as a microcosmic model for the whole planet, to warn against the eventual exhaustion of natural resources by overexploitation [33]. An alternative proposal suggested that deforestation would have been caused by massive consumption of palm fruits by human-transported Polynesian rats, which prevented forest regeneration [34]. This hypothesis was based on the frequent finding of palm fruits with evident signs of rat gnawing in archeological sites. According to this view, the ecological catastrophe and the cultural collapse were not causally linked, as the ancient Rapanui civilization remained healthy after forest clearing and its collapse was actually a genocide that occurred after the European contact (CE 1722), owing to slave trading and the introduction of previously unknown epidemic diseases [35].

Human resilience to deforestation has been supported by varied archaeological evidence suggesting improved land-use practices and no significant demographic declines between forest clearing and the European contact [36–38]. In addition, the genocide is well documented historically [35]. From this point, two dual deterministic debates on the causes of deforestation—either humans or rats—and the collapse of the ancient Rapanui culture—either the Polynesians themselves or the Europeans—started. As it occurred with the testing of the ecocidal ruling theory, these controversies have been addressed under a confirmation, rather than a falsification, approach. This means that the proponents and the defenders of the different options have always been looking for empirical evidence to support their respective hypotheses assuming that this was enough to implicitly refute the others, which is incompatible with Popperian falsification.

### *5.3. Human Determinism*

Some authors suggested that eventual climatic events, notably droughts, that occurred during the LIA could have had some role in both ecological and cultural collapses [39,40]. However, this was dismissed with the argument that the forests had been continuously present on the island during the last ≈40,000 years, which included the Last Glacial Maximum (LGM), a longer and more intense climatic shift than the LIA [41]. In addition, the lack of palaeoclimatic records from the island prevented the testing of hypotheses based on climate change. As a result, the history of Easter Island since its original human settlement has always been considered under a human-deterministic approach (Figure 5). However, none of the existing proposals about the first settlers and the causes of the ecological and human collapses have explicitly been falsified and, as a consequence, they have survived until today. The danger of not falsifying alternative hypotheses is that, sooner or later, new evidence may come to light that challenges the current paradigm and revives older proposals or requires new explanations. This has occurred recently with the ruling theory of the assumedly unique colonization of Easter Island from Polynesia, mentioned above, and also with the dual controversies about deforestation and cultural change.

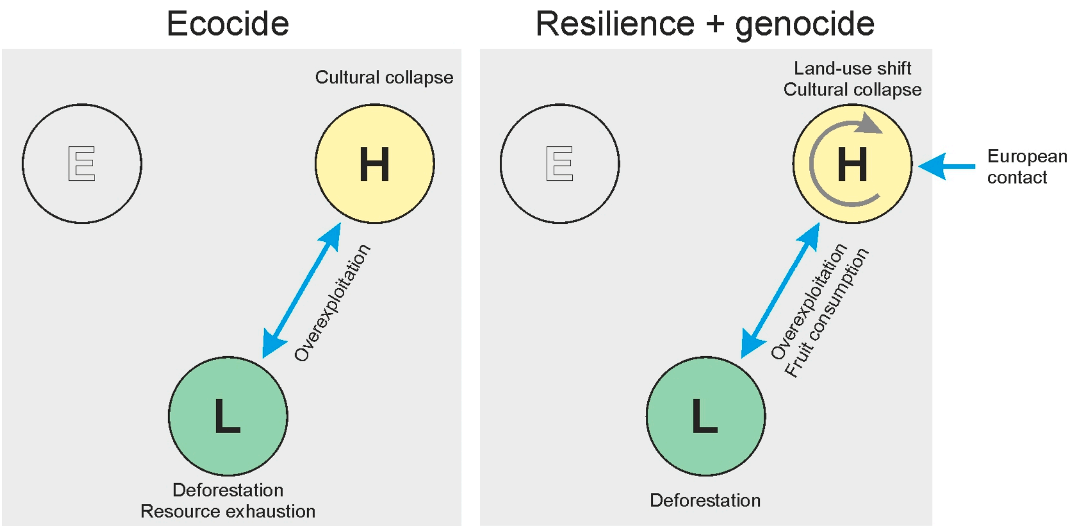


**Figure 5.** Human-deterministic approaches to Easter Island's deforestation and cultural collapse under the EHLFS framework. See Figure 2 for details.

### *5.4. New Challenging Evidence*

The recent development of molecular analytical techniques has provided novel observations that were not possible to obtain before. For example, the analysis of the DNA from modern Rapanuis has demonstrated that they actually have Amerindian inheritance and that the Polynesian–Amerindian contact could have occurred between CE 1280 and 1495, that is, shortly after the assumed Polynesian colonization [42]. It is still unclear whether such contact took place in Easter Island or in South America, as some evidence exists on the possibility of Polynesians travelling to South America before its European discovery [43]. The possibility of Amerindians arriving at Easter Island before the Polynesian settlement would be supported by the finding of pollen from the American weed *Verbena litoralis* Kunth as early as BCE 400–500 [44]. This revives Heyerdahl's ideas to some extent and shows that archaeological, ethnographic, linguistic and historical evidence utilized before to support a unique Polynesian colonization was insufficient to falsify the Amerindian option. Something similar occurs with the dismissal of eventual climate shifts as potential drivers of ecological and cultural change.

During the last decade, palaeoclimatic and palaeoecological research on Easter Island has intensified and new evidence on climatic and landscape changes is now available. Concerning the climate, two main arid phases have been documented during the last millennium, the first during the MCA and the second during the LIA, with a wetter phase between them [44]. The LIA drought is especially interesting, as it occurred between CE 1570 and 1720, which roughly coincides with the time interval between the disappearance of the *moai* culture and the European contact [45]. This drought is manifested in the drying of Lake Raraku, the *moai* quarry. Another relevant finding was that deforestation did not occur in a synchronic fashion across the island. The catchments of the three coring sites studied—lakes Kao and Raraku, and the Aroi bog—were deforested at different times and proceeded at different rates. In Raraku, forest clearing initiated by BCE 400–500 and intensified by CE 1200 ending by CE 1450 [44]. In Kao, two deforestation events have been documented; the first at about CE 100 and the second between CE 1400 and 1800 [46]. In Aroi, deforestation lasted about a century, between CE 1520 and CE 1660 [47]. This can be considered an explicit falsification of the previously assumed synchronous, abrupt and total deforestation of the island, which is one of the foundations of the ecocidal ruling theory. Combining this new evidence on climate change and deforestation patterns with the formerly available palaeoecological, archaeological and historical evidence in an EHLFS framework, a different view of Easter Island's ecological and cultural history emerges, which is compatible with most empirical observations [48].

### *5.5. A Fuzzy EHLFS Approach*

The EHLFS approach considers that both climate and humans affected the landscape, and that the resulting feedbacks and synergies among these three elements triggered the shift from the *moai* culture to the Birdman culture and the associated cultural change. This holistic proposal should be considered a fuzzy multiple-working-hypotheses scenario to be tested with further studies. Currently, this framework is based on palaeoecological, archaeological and historical evidence available to date and tries to account for as many empirical observations as possible from these fields. However, further studies can boost this framework or modify it, as new empirical evidence becomes available. The graphical display of the Easter Island EHLFS approach, as used here, is shown in Figure 6, and is explained as follows.

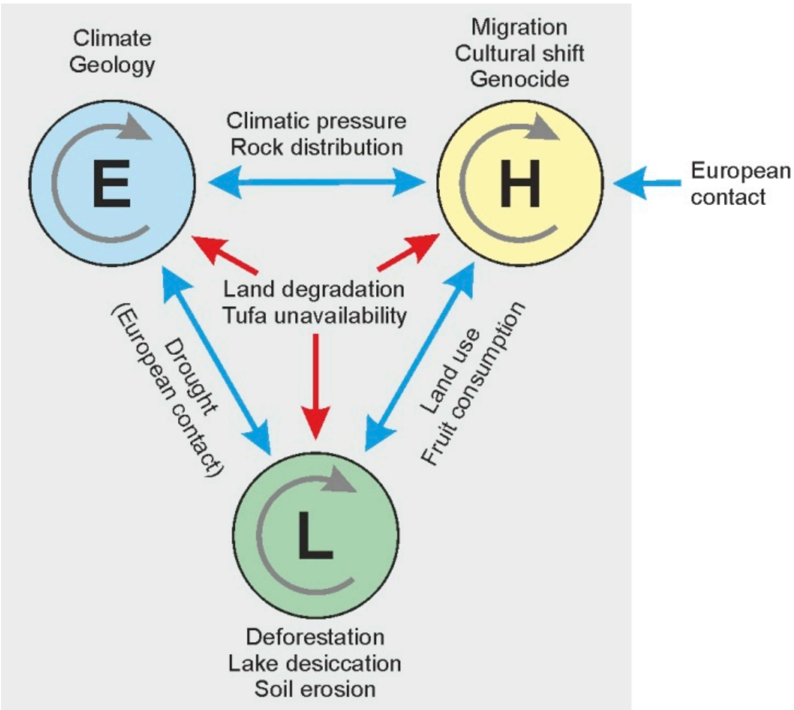


**Figure 6.** EHLFS holistic approach for Easter Island's ecological and cultural changes, as is suggested in this paper. See Figure 2 for details.

The flourishing of the *moai* culture coincided with the wet climatic phase which occurred between the MCA and the LIA (CE 1200–1550), but further human activities and environmental events led to its disappearance. The Raraku basin was totally deforested by CE 1450 [44], which coincides with the last signs of cultivation [49]. Before those dates, agriculture and *moai* carving coexisted in a forested landscape with favorable climatic and ecological conditions and a lake similar to the present, which provided the freshwater needed for cultivation and human consumption [48]. Deforestation would have been caused by anthropogenic felling and burning, by rats, or by both (i.e., the dual determinism between either humans or rats as the driving agents is actually a fake dualism, as these hypotheses are not incompatible). As mentioned above, amplification feedbacks between landscape opening and local microclimates would have increased vegetation flammability thus exacerbating fires, and increased soil erosion would have hindered forest recovery. This, combined with the subsequent drying out of the lake by CE 1570, would have transformed the catchment into a wasteland devoid of freshwater and unsuitable for human life, a situation that lasted until CE 1720, shortly before the European contact. Again, positive feedbacks between climate and landscape features would have existed.

In these conditions, the Rapanuis would have been forced to abandon the Raraku catchment and migrate to other locations where forests and freshwater were still available, which would have determined the end of the *moai* carving around Lake Raraku. There is no evidence of structures such as channels or aqueducts to transport water across the island, which suggests that the Rapanuis lived close to the available freshwater sources. The whole picture suggests that environment–human synergies, and the corresponding internal and external feedbacks, led to an unsustainable situation that triggered internal feedbacks in the human society, in the form of intra-island migration. Similar internal migrations during the LIA have been reported for many other Pacific islands, where they followed a typical coastal-to-inland pattern [19]. On Easter Island, migratory behavior is consistent with archaeological evidence showing spatial shifts in cultivation patterns from drier and infertile areas to others more suitable for agriculture [38].

The only options for human migration, in the search for freshwater, were the Aroi or the Kao catchments. No evidence of large-scale permanent settlements around Aroi is available during the LIA drought but some observations suggest that some migration from Raraku to this bog would have existed. The Aroi forests started to be cleared by CE 1520 [47], which is an intermediate date between the deforestation of the Raraku catchment (CE 1450) and the drying out of its lake (CE 1570). Aroi deforestation was complete by CE 1660 [47] and the last signs of human presence were recorded by CE 1650 [50]. In summary, some marginal human populations would have been living around the Aroi bog between CE 1520 and CE 1650, possibly escaping from the degraded Raraku landscape, and they abandoned the site shortly after its total deforestation. None of the *moais* present on the island are known to have been carved on rocks from the Aroi catchment [51].

The Kao is the largest and deepest lake of the island and did not dry out during the LIA [52]. Hence, this seems to have been the better place for the ancient Rapanuis to migrate to, in terms of water availability. Regarding forests, they seem to have also been present in the Kao basin during the phase of Raraku desiccation [46]. The available archaeological evidence suggests that permanent and quantitatively significant human occupation of the Kao basin started around CE 1600—just some decades after the LIA drought that desiccated the Raraku lake—with the foundation of the ceremonial village of Orongo, the center of the Birdman culture [53]. The Kao catchment is modeled on basaltic rocks, which are too hard for *moai* carving. Actually, only a dozen of the ≈900 *moai* are known to have been carved on basalt [51]. The difficulty of carving *moais* on Kao rocks with the available technology would have contributed to the end of this culture and the development of the Birdman culture. Therefore, a new synergistic effect between human developments, in this case migrations, and environmental constraints, in this case geology, would have occurred leading to a profound social transformation. Internal human feedbacks were manifested as a change in sociopolitical and religious organization. By CE 1720, wetter climates returned and Lake Raraku replenished but forests never recovered [44]. Shortly after, the Europeans arrived to the island and opened a socioecological system that had remained closed for centuries (Figure 6). From this point, the external influence was dominant and guided further cultural developments, including the genocide of the Rapanui civilization. Therefore, the potential effects of further eventual climate changes on the local society were obscured by human impact.

Under a holistic EHLFS model, human responses to their own pressure combined with environmental forcing, as well as their mutual feedbacks and synergies, are regarded as mostly adaptive. In a first stage, LIA drought and deforestation would have led to improved land-use and intra-island migrations, as a combined adaptive strategy [38]. In a second stage, migration patterns and geological constraints would have determined a significant cultural shift. In this second case, the eventual adaptive meaning is not self-evident and needs further consideration. The ancient Rapanui culture represented by the *moai* culture was based on the perennial dominance of a dynasty-based authority descended from the original island settlers, that is, the *Miru* clan [28]. Such sociopolitical organization seems to be well suited to thrive under more or less stable environmental conditions represented by the steadily wet climates recorded at Easter Island since the Polynesian settlement [45]. The Birdman culture, on the contrary, was based on a permanent renewal of the main authority of the island, which was reconsidered yearly after an athletic competition among all the clans of the island [28]. This system, based on short-term governmental shifting, rather than on immutable dynasty-based criteria, seems more appropriate for unpredictable environmental conditions as those experienced by the Rapanui society after the coming of the LIA drought, which should have been a kind of surprise if compared with the former environmental stability [48].

In a third stage, the external pressures from alien human cultures after European contact became major drivers of cultural shift. These influences, although anthropogenic, could be viewed as environmental drivers, as they are external influences independent of the internal Easter Island's cultural developments. For the Rapanuis, European contact could have been similar to extraterrestrial visits to the Earth in our present context. Alternatively, European contact could be considered an external forcing that disrupted the, until that moment, closed Easter Island socioecological system. Direct climatic pressure on the Rapanui people and the corresponding adaptations cannot be dismissed. Climatic stress may force humans to modify their lifestyle in aspects such as clothing, dwelling, outdoor activity, and so on. The first Europeans who arrived on the island, close to the end of the LIA drought, noted that the Rapanuis lived mainly within caves formed by lava tubes, which contrasts with the abundant remains of outdoor houses that were used by the ancient *moai* civilization [54]. Several hypotheses related to social conflicts and personal safety have been proposed to explain such change, but a strategy to escape from climatic aridity by living on unexposed and likely cooler and wetter underground dwellings (note that most of the fresh water of the island runs sub-superficially, as explained above) should not be disregarded.

The EHLFS proposal does not make any explicit demographic predictions and is compatible with several scenarios of human population dynamics, except, perhaps, the ecocide. The ecocidal model suggests an exponential population increase since the initial settlement (CE 800–1200) up to about 15,000 inhabitants by CE 1600, followed by a sharp decline to less than 2000 inhabitants by the time of European contact. The genocidal model assumes a maximum of 4000 inhabitants by CE 1300–1400, which persisted until the end of the 18$^{th}$ century and an ensuing decline to 1000 inhabitants due to alien human pressure. A combined model proposes rapid population growth until 7000 inhabitants by CE 1400 followed by a gentle and gradual decline to 2000 people by CE 1800 [55]. It would be interesting to develop new modeling attempts based on the EHLFS framework.

### *5.6. Strong Inference*

As mentioned before, new studies could lead to changes in the EHLFS framework, as presented here. This is one of the requirements of strong inference, which is aimed at looking for alternative hypotheses to be falsified, in a Popperian sense. Therefore, the next step is to test the approach illustrated in Figure 6 using the strong inference method. Some examples exist of alternative ways of thinking that should be taken into account in future research. For example, some believe that the Birdman culture could be more recent than actually thought, and they relate this cultural manifestation with the European contact [53]. Others have suggested that the more significant population reduction took place over barely 50 years, between the visits of the Dutch Jacob Roggeveen, the first European expedition that arrived on the island in 1722, and the British James Cook, who landed in 1774 [35]. Other views exist and many others can emerge in the future but the EHLFS framework seems to be sufficiently robust to provide a useful research environment able to accommodate most evidence and interpretive approaches.

## 6. Final Remarks

The usefulness of the strong fuzzy EHLFS approach will only be appreciated after its application to as many case studies as possible, which also will contribute to its improvement as a theoretical research tool. One of the reviewers pointed out that some researchers are already using similar approaches and the value of this paper is to have the conceptual framework structured and published for reference. I celebrate this and hope that the use of this and other similar research approaches will increase with time and replace too-simplistic approaches to complex issues.

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