ECOLOGICAL ECONOMICS XX (2008) XXX–XXX

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Bridging ecological and social systems coevolution: A review and proposal

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ARTICLE DATA

Article history:
Received 25 March 2008
Received in revised form 19 July 2008
Accepted 23 July 2008

Keywords:
Coevolution
Cultural evolution
Biological evolution
Systemic influence

ABSTRACT

Social and Natural sciences have, for the most part, ignored the existence of interlinked/interdependent evolutionary processes between cultural and biotic systems, both embedded in an overall dynamic biophysical environment. In this paper, we explore the potential of filling this gap by further developing a common coevolutionary framework based on earlier work in ecological economics. Our main concern is to contribute to the understanding of socioecological coevolution in two ways: (1) to find a general framework that accommodates advances in the explanation of sociocultural evolution in social sciences and, (2) to identify the specific mechanisms that could link this knowledge to what is known in the biological sciences.

> "… this traditional dichotomy of humanity-versus-nature is false and dangerous. On the one hand, it perpetuates our destructive mishandling of the biosphere. On the other hand, it scants the self-understanding that Homo sapiens needs to settle down on our home planet, hence as a prerequisite to survival. Nature, to put the matter as succinctly as possible, is part of us, and we are part of nature." E.O. Wilson (2007: xiii)

1. Introduction

Socioecological systems (Folke et al., 2005) can be thought of as changing through coevolution between their social and ecological components (Norgaard, 1994). Yet, while this can be understood intuitively, theory and empirical analyses remain undeveloped. There is a well-developed, cohesive biological literature on the coevolution of species within ecological systems. Coevolution at other levels and scales is admittedly more controversial. With neither the social science equivalent of a Darwin nor a Mendel, however, the social science literature on the coevolution of components of social systems is noticeably less developed and far less cohesive than the biological literature. The social sciences have struggled with multiple, incompatible constructs. Neither the biological nor social science literature, however, helps us understand how: (1) evolving sociocultural systems are increasingly affecting their biophysical environment nor (2) how evolving ecological systems are increasingly affecting sociocultural change. The challenge to understanding socio-ecological coevolution is thus two fold: (1) to find a general framework that accommodates advances in the explanation of socio-cultural evolution in social sciences and, (2) to identify the specific mechanisms that could link this knowledge to what is accepted in the biological sciences.

Evolution is a process of change over time and space. For living systems, Darwin (1859) characterized it as a matter of *descent with modification*. In biology, the process of genetic inheritance among individuals across generations driven by natural selection has been emphasized. Here "natural" refers

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doi:10.1016/j.ecolecon.2008.07.020

to the biophysical environment surrounding a particular species. Biologists have traditionally focused on evolution in more or less *undisturbed* environments. There are two very important reasons for this: (1) human culture did not come into play until very recently and, (2) people have greatly modified the environment and thereby the course of biological evolution. So, if the basic question — How did life evolve on earth? — is central, it follows that natural undisturbed environments are a precious resource to answer that question (Thompson, 1994). While restricting the "environment" to "natural" systems helps biologists understand important evolutionary processes, it also blinds evolutionary biology to the increasingly relevant processes of evolution in the context of human action. To understand our biological future, we need to understand how human culture is affecting both, the course and the laws of evolution. Of course, some biologists are beginning to address this, but the overall effort is still very low.

In the social sciences, efforts to understand evolution within cultural systems have been, and still are, a quite complicated inquiry. On top of this, bridging the gap between the understanding of human evolution in a biological sense and human evolution in a cultural sense continues to be difficult and to generate controversy.

As the evolution of cultural systems seems to accelerate its destructive influence on our planet, there is a clear need to unveil the links between the units, the systems and the processes of cultural and biological evolution. Knowledge of them could provide us with important — not to say vital — clues on how to change social institutions and technologies in accordance with, not only more ecologically driven ethics, but the long term interest of our species. In summary, we urgently need to understand the coevolutionary character of culture and nature and incorporate it into our technology and social organization. This particular issue is at the heart of this paper. Unfortunately, it is also at the core of most conflicts that divide the natural and social sciences. Thus, the main goal of this article is to propose an overarching coevolutionary framework capable of both: (1) bridging the theoretical gaps between the biological and social sciences, and (2) contributing to the understanding of the biophysical impacts of cultural systems through the study of the relevant units and forces operating between two on going coevolutionary processes: cultural evolution and biological evolution.

We provide a short review of the major issues concerning evolutionary theory in the biological and social sciences in Section 2. Then, in Section 3, we critically analyze the development of coevolutionary thought in ecological economics. In Section 4, we propose a basic common coevolutionary framework, define its basic characteristics and dynamics, propose a tentative method to structure and study coevolution through a series of specific examples, and try to specify some general theoretical implications of our analysis. Finally, we summarize our results and concerns in a concluding section.

2. Evolutionary theory in the biological and social sciences. A review summary

In biology, evolution is defined as the "change in the frequencies of genes in a population of individuals from one generation to the next" (Pagel, 2002: 330). Some change occurs through random mutations and drift, some through differential migration of individuals, and some through what Darwin called natural selection. The distinction in evolutionary biology between evolution and evolution by natural selection arose through the grand synthesis in mid 20th century between biology and genetics (Mayr, 1982).

One of the main problems within evolutionary biology is agreeing on the plausibility and importance of selection at different levels. While evolution at the level of the individual organism is completely accepted and empirically documented (though perhaps conflated with evolution at other levels), arguments for evolution at other levels are more contentious, while the difficulties of empirically sorting out levels of evolution is more difficult. The levels range from the gene (Dawkins, 1976), the group and the importance of social interactions (Wilson, 1998), and the species within geographical landscapes or in macroevolutionary terms (Thompson, 2002; Gould, 2002).

Coevolution has been largely characterized as a reciprocal evolutionary process between interacting species driven by natural selection (Thompson, 2002). At its narrowest conception, it refers to the specific, reciprocal, simultaneous evolution of traits between two closely related species. The loosening of one or some of these requirements provides degrees of flexibility in the definition while confounding the difficulties of empirically sorting out the processes. At a broader level, coevolution might be defined as *diffuse coevolution*, meaning the adaptation of species to multiple features of their biotic and physical environment (Futuyma and Slatkin, 1983). Coevolution is important because it links evolutionary biology to ecology. It opens evolutionary theory to the identification of more precise selective relationships among species in evolutionary explanations, however, it also opens our understanding of evolution to a rich interactive complex of processes that vary across landscapes, making distinctions between the selective processes more difficult.

Another dispute shaping modern evolutionary theory has been the need to explain punctuated equilibria and rapid change at the species level (Gould, 1992). This is interlinked with the distinction between Microevolution (as explained by Darwin) and Macroevolution (compatible with Darwinian evolution). Macroevolution ideas have widened a huge area of collaboration between evolutionary biology and other physical sciences. This is of particular relevance because the Darwinian theory of evolution is now being placed within the context of new findings that improve our understanding of the relationship between Earth's dynamic processes and the evolution of life. Here, the distinction between physical (abiotic) and biological (biotic) systems or factors in evolution must be addressed, since "Macroevolutionary patterns are shaped by both physical and biotic factors, and the rich feedbacks between them" (Jablonski, 2003: 247). However, this distinction is not always easy, as for example in the case of climate. As Rothschild and Lister (2003: X) put it, in the history of evolution there are "complex interactions of physical and biotic factors (…). It is clear that a full understanding of evolution must emphasize both aspects (…). Adaptations to the physical environment are of equal importance and remain the subject of much research".

Please cite this article as: Gual, M.A., Norgaard, R.B., Bridging ecological and social systems coevolution: A review and proposal, Ecological Economics (2008), doi:10.1016/j.ecolecon.2008.07.020

All these ideas are important to the paper because the process of cultural evolution probably affects evolutionary processes at all levels of selection.

Evolutionary thought in the social sciences is more dispersed and less integrated than in the biological sciences. The evolution of human societies and culture has been a contentious issue in anthropology since Morgan's stages from Savagery–Barbarism to Civilization. "This deeply ethnocentric belief", contend Johnson and Earle (2000: 3), "had two components that came under attack separately at quite different periods in the history of evolutionists thought. The first component was a racist assumption that progress in science, technology, law (…) was intrinsically linked to race: inferior races could not aspire to the higher levels of achievement because they were incapable of it.[1] The second component was the nature of progress itself, the question of who, if anyone, benefits from the changes we call socio-cultural evolution". The first reaction to the link between race and progress came from Boas (1945 [1920]) and the counter movement known as relativism that provided both, evidence of the irrelevance of race to explain cultural differences, and the denial of social evolution (Service, 1971). This denial, however, was not an absolute statement. As Kroeber's (1948) work (and others in the relativist school) show, the study of the particularities of different communities and cultures facilitated a fine pool of empirical evidence for understanding some aspects of cultural evolution.

Steward (1953: 313) argued that "cultural evolution is an extension of biological evolution only in a chronological sense. The nature of the evolutionary schemes and of the developmental processes differs profoundly in biology and in culture". Furthermore, Steward distinguished between unilinear (19th century) evolution, universal evolution, and multilinear evolution. While unilinear evolution placed cultures in stages of universal sequences, universal evolution tried to find common patterns and processes that could be used to discover "general laws descriptive of the evolution of all societies …" (Childe, 1951: 35). Alternatively, Steward (1953) proposed a rather more bottom-up approach, from the particular to the general, using the idea of multilinear evolution as a way to bridge between the apparent diversity of cultures and the significant regularities found in processes of cultural change. He soon realized, though, that "the outstanding methodological problem of multilinear evolution is an appropriate taxonomy of cultural phenomena" (Steward, 1953: 320). This—still unsettled—problem with respect to a suitable taxonomy of the determinants of human decisions and social evolution was extended by the relatively recent incorporation of findings from evolutionary social biology and psychology. These findings show that while rational theory is not a good predictor for an individuals' decision, there are very basic biological — genetic — evolutionary imprints that bound human behaviour (Boyd and Richerson, 1985). Therefore, it follows that human decision-making as a unit for socio-cultural evolution is a more complex process than either a rational utilitarian problem or an exclusively socially instituted one. Neuroscience, evolutionary psychology and socio-biology are documenting that the brain is not a "white blanket" that the environment (and culture) completely shapes, but rather it seems to have the historical imprint of evolution, providing us with differential innate qualities (Wilson, 1998). Caspi et al. (2002: 853) provide empirical evidence supporting this statement in a study showing that "males with low-activity MAOA (monoamine oxidase A) genotype who were severely maltreated developed some form of antisocial behaviour". Furthermore, Sanes et al. (2006: 291) argue that

> "neural activity modulates the expression of the same gene products that were used during neural embryogenesis. This interplay between the environment and the genome continues throughout life. And because of this, it is usually not reasonable to ascribe specific behaviors to purely genetic or environmental determinants. Genetic influences on behavior are as clear as experiential ones, and the two are interlinked".

This implies that when neural structures start developing in an embryo, many gene-combinations seem to be triggered in response to environmental conditions, affecting in many different ways the developmental process of the brain itself and of its informational capabilities.[2]

While acknowledging this link is of utmost importance to understand what Wilson called "human nature", it is also essential to keep in mind that the complex of neuron interactions that constitute the material basis of the adult human mind (with all its gene-environmental roots) show emergent properties — differential human ideas — that both, influence and are influenced by ideas and social structures; that is, by culture(s) in a broad sense, and by the biophysical systems in which cultures are embedded. Whilst these emergent properties are inextricably linked to the developmental process of the nervous system, they also seem to show their own complex developmental path. The process by which these "emergent properties" are reflected upon the biophysical system, we call cultural evolution (in a very broad sense). The result is "culture" at any given moment in time and space. Developing this overgeneralization, Durham (1991: 3), following Geertz (1973), proposed — along with four other properties — that

> "culture consists of shared ideational phenomena (values, ideas, beliefs, and the like) in the minds of human beings. It refers to a body or pool of information that is both public (socially shared) and prescriptive (in the sense of actually or potentially guiding behavior)".

Multilinear evolution (Steward, 1955), ideational theory (Geertz, 1973), and the acknowledgement of the gene-culture continuum (Durham, 1991) provide a proper framework to zoom into the particular institutions, technologies and markets that have developed through cultural evolution.

[1] A complete tale of this first component of 19th century racism can be found in Gould's (1981) "The mismeasure of man".

[2] As Sanes et al. (2006) cite, one of the clearest examples of this cause-effect is the influence of drug-use or alcohol during pregnancy leading, many times, to mental retardation (Johnson and Leff, 1999).

In economics, Simon (1947) suggested that individuals made their judgments within a bounded rationality, so rather than optimal decisions it was more proper to speak of satisfying decisions. The idea about the process of adaptation and creative response in economics (Schumpeter, 1947) became the inspiration for further developments in evolutionary thought ranging from Arrow's (1962) "learning by doing", Nelson and Winter (1977) and Dosi (1982) "technological regimes or paradigms", David (1985) and Arthur (1990) "technological lock-in", and Freeman (1987) "National systems of innovation". Nelson and Winter (1982) provided the basis for an alternative characterization of decision-making processes based on 'routines' which were depicted as mechanisms that are transmitted within organizations.

While the use of Darwinian analogies and metaphors has been quite useful in explaining processes in organization theory (Porter, 2006) and industrial organization and technical change (Nelson and Winter, 2002), there is concern about the use of biosciences language. There are two basic issues that need to be distinguished: (1) the concerns about the extended (metaphoric) use of Darwinism in social sciences (within the limits of cultural systems), and (2) the overall problems, — ontological and semantic — that arise when non-metaphoric links between the processes of cultural and natural evolution need to be addressed.

The first question has been extensively discussed in recent literature, and concerns the ontological use of Darwinism in social sciences. On one hand, Hodgson and Knudsen have repeatedly proposed that there are several Darwinian ontological principles that can be applied to social sciences — a sort of Universal Darwinism — (Hodgson, 2004) and have, in many ways, provided quite convincing arguments about the usefulness of such general conceptions. On the other hand, Witt (2004: 141) has argued that the abstract transposition of Darwinian principles to cultural evolution is both inadequate and problematic. Instead, he has proposed a continuity hypothesis where

> "there is a historical, ontological continuity in which evolution in nature shaped the ground and defines the constraints for the various other forms of cultural evolution", but that "the mechanisms and regularities of cultural evolution differ fundamentally from those of natural evolution. Darwinian theory is therefore not sufficient to explain them. The many facets of cultural evolution require explanatory theories of their own".

These somewhat contrasting views have spurred much cross argumentation. For instance: Buenstorf (2006) defends an empirically based universal Darwinism, Cordes (2006: 538) — following Witt (2004) — points out that "the metaphorical use of Darwinian principles risks concealing the real mechanisms underlying economic and cultural evolution". Furthermore, a more general debate on the appropriate ontological characterization of evolutionary theory in social sciences has also been intense (see: Klaes, 2004; Vromen, 2004; Dopfer and Potts, 2004).

This ongoing discussion, while making interesting points, seems to slow down the efforts to devise a better understanding of sociocultural evolution. As many scholars from different disciplines have already noted, there are important fundamental differences in the processes of cultural and biological evolution. Simon (1980: 74) made clear that "while the Darwinian metaphor has been stimulating and useful, the current interest in evolutionary models of social phenomena demands a careful building of theory from the ground up, with the closest attention to the initial assumptions about the mechanisms". More recently, Nelson (2006: 498) has expressed the same concern: "it would be a mistake to simply assume that the details we now know about the mechanisms behind evolution of species carry over to these other areas. Some may. Some may not".

The second issue refers to the quite challenging ecological economics proposal of using coevolution in an integrated manner to better understand how institutions and policies affect sustainability. Ecological economists use coevolutionary thinking to explore how the evolution of cultural systems affects and is affected by the overall biophysical system and, in particular, how it is literally modifying evolutionary processes (as conceived in the biosciences) guiding all living species.[3] Thus, we now turn to the main contributions of ecological economics regarding sociocultural and biological evolution.

3. Ecological economics: toward a coevolutionary understanding

Ecological Economics is, among other things, an evolutionary science. Norgaard (1981, 1984a,b) provided the first steps toward a general coevolutionary framework to explain the reciprocal evolution of sociosystems and ecosystems driven by mutual selective processes. He linked developments in evolutionary biology with many contributions from other social sciences. Later, Norgaard (1994: 40–44) wrote:

> "…social and environmental systems coevolve such that environmental systems reflect the characteristics of social systems — their knowledge, values, social organization, and technologies — while social systems reflect the characteristics of environmental systems — their mix of species, rates of productivity, spatial and temporal variation, and resilience. The coevolutionary description of development explains why, and to some extent how, everything is related to everything else".

At the same time, Gowdy (1994) explored the potential of this idea, and incorporated the notion of punctuated equilibria and sudden change from evolutionary biology into the broad discussion of the interactions among economic and environmental systems. Norgaard and Gowdy established the basis of a broad coevolutionary approach, exploring the reciprocities between evolutionary (or coevolutionary) processes in ecosystems driven by natural selection, with change in other

[3] We refer to both, the systemic impact of socio-cultural development on the environment and the implications derived from the use of genetic techniques on the evolution of certain species.

systems (cultural, social, institutional, technological, etc.) driven by other complex evolutionary mechanisms.

More recently, Van den Bergh and Stagl (2003) have pointed to the potential of coevolution as an analytical framework to study institutions and institutional change and its links to biological evolution. They defined four layers of interactions: *genetic, individual, group, and institutional*.

At the micro level, Gowdy and Erickson (2005) and Gowdy (2007) show how many new experimental and empirical results coming from psychology, game theory, sociology, and other related fields conflict with Walrasian tenets. This is reshaping analytical conceptions about the role of economic actors in development, and providing new support to a coevolutionary understanding of economics.

Faber et al. (1996) and Giampietro (2003) discussed the Lamarckian character of cultural evolution in the context of ecological economics. Winder et al. (2005) argued for the need to better specify and narrow the coevolutionary concept, distinguishing it from co-dynamic change, and stressed the Lamarckian nature of institutional change. In "when it is coevolution?" Kallis (2007a) tried to clarify some misunderstandings found in Winder et al. (2005) and to refine the distinction between coevolutionary processes and co-dynamics. Kallis (2007b: 6) critically argues: "Coevolution in these articles is used as a synonym for co-dynamic change of social and environmental variables or feedbacks and impact-responses between broadly defined social and environmental systems (…) They did not exploit the promises of coevolution to erode society–environment or design–chance dualisms." He supports the idea of working with a general coevolutionary framework in the search of empirical cases, with the hope of better understanding complex ecological–economic relations. He suggests three important issues to account for (within ecological economics) when applying coevolution: (1) specify variation, (2) explaining interactions and selection and, (3) combining coevolution with other modes of explanation.

Stagl (2007) defines three main layers of coevolutionary processes that are relevant in the context of sustainable development: (1) Coevolution of the environment and governance; (2) coevolution of technology and governance, (3) Coevolution of human behaviour and culture. Within this institutional context, Farrell (2007) looks at the recursive coevolution of values and valuations, focusing on the problems derived from a preference-based monetary valuation in the realm of priceless environmental values.

Noailly (in press) develops a mathematical model with bounded rationality agents, whose economic activity selects for genetic traits in successive pests populations. While very interesting, the limitations of mathematical modeling in this area are big, and they are somewhat implied by the extended (more than what can be deduced from the modeling results) recommendations the author makes.

Cairns (2007: 107) expands the strict biological definition of coevolution to incorporate other systems: "The basic definition of coevolution is 'the simultaneous development of adaptations in two or more populations, species or other categories that interact so closely that each is a strong selective force on the other' (Raven and Johnson, 1986)". He proposes the idea of "mutualistic coevolution" in the same way that Norgaard (1984a) proposed the idea of "coevolutionary development potential", both meaning reciprocal evolutionary changes that favor the reproduction and survival of each Partner or system. Finally, he points to the capacity of nature to react in catastrophic ways (climate change or pandemics) to the stress to which cultural evolution is submitting it.

Goldstein (2007) explains some of the challenges of the coevolutionary paradigm in view of the different conceptual meanings of the word in biology and in artificial life (non-biological entities). When using the term metaphorically, he finds two basic problems that need to be addressed in a coevolutionary study: (1) Framing the nature of the interactions and (2) The unit of interaction between systems. He rightly points that the there is a similar lack of consensus about the appropriate units of selection in natural sciences (gene, individual, group, species…) and in other more metaphoric applications.

In their summary conclusions on reviewing most of the abovementioned articles, Rammel et al. (2007) point out the lack of empirical studies of coevolution within ecological economics compared to organization theory or industrial organization, and the challenge of going forward in that direction.

In the next section we try to synthesize and propose some basic tenets of a common coevolutionary framework making compatible the biosciences and social sciences knowledge of evolution.

4. A proposal on a common coevolutionary framework (theory)

The basic purpose of a coevolutionary theory is to find a way of conceptualizing how interdependent/interlinked processes going on in the cultural and biotic systems affect each other in the context of the complex dynamic characteristics of the overall biophysical system.

4.1. *Framing coevolution*

A useful way of looking at coevolution is to distinguish between systems and processes. In the model we present (Fig. 1), we define three embedded systems: biophysical, biotic and cultural. All three systems have multiple complex links bounding them together that can only be analyzed, and partly grasped, through specific studies. However, all these systems evolve, and the processes by which they do are interconnected and, to a great extend, interdependent. The focus of coevolutionary theory is the study of both, (1) what are the basic units, characteristics and modes of each one of these processes, and (2) how these processes relate to one another creating the systemic coevolution that seems to be shaping life in our planet.

4.1.1. *The biophysical system: mutually compatible processes*

At the most general level, Darwinian theory is accommodated within a macroevolutionary understanding of evolution. For the purposes of this paper, several conditions derived from this view become relevant: (1) biotic and abiotic factors are determinant in microevolutionary processes. Taken to an extreme this may lead to the Gaia hypothesis: "the coevolution of the biota and the oxygen content of the atmosphere over

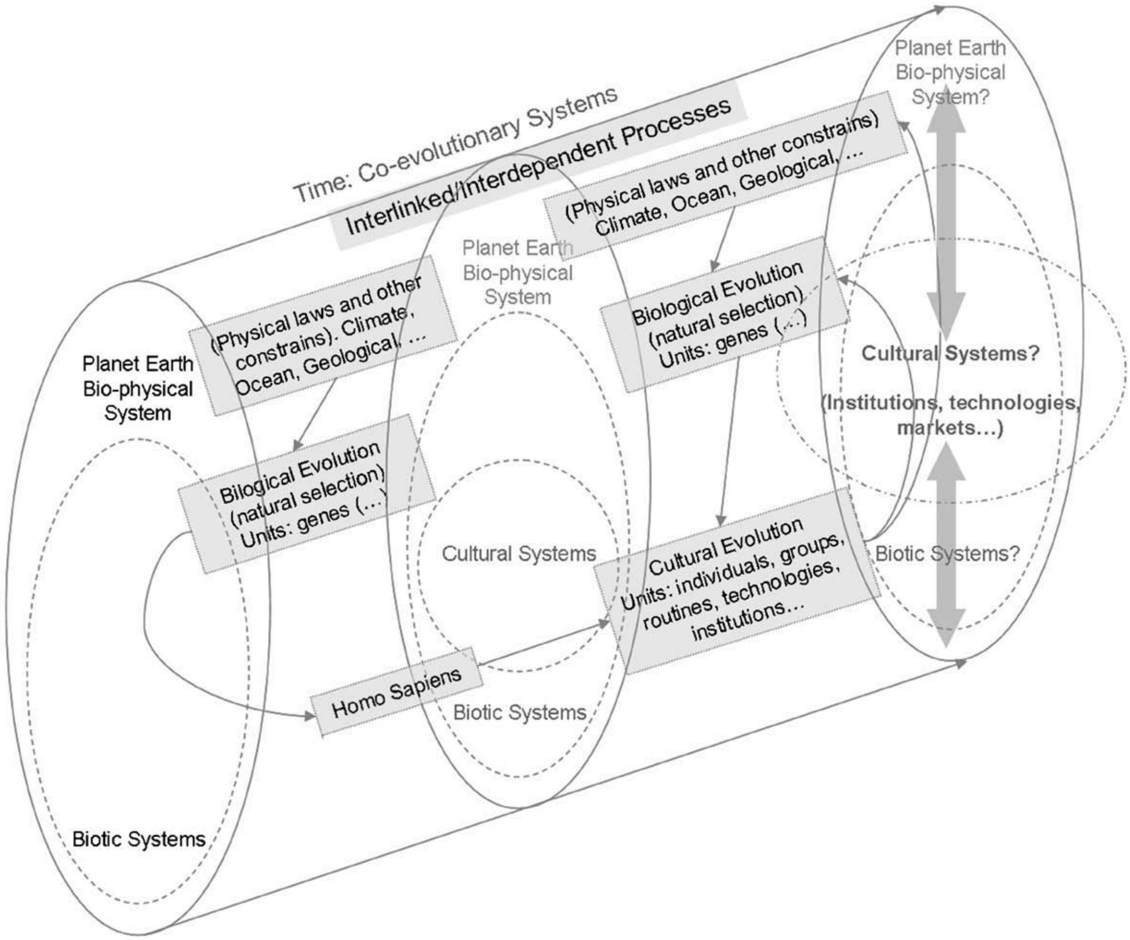

Fig. 1 – Conceptualizing coevolution.

earth history, the increase in free energy and biotic activity, and the emergent self-regulation of the coupled system support the Gaia theory (Lovelock, 1995; Lenton, 1998)" (Lenton, 2003: 51). (2) Sudden events can potentially and radically change evolutionary paths, and (3) the process of cultural evolution has become a macroevolutionary force.

4.1.2. *Biotic systems and processes*

At the microevolutionary level, genes, individuals, groups and species seem all to be, to some extent, subjected to selection forces in the biophysical environment. The extent to which cultural evolution influences and becomes influenced by this process at all levels is a main area of inquiry of coevolutionary theory. One important aspect to take into account here is the relative conception of temporal and spatial scale in evolution. As Gavrilov and Gavrilova (1991) show there are many different quantitative measures of life span. Some refer to metabolic rates and aging times, other to reproductive rates, etc. These facts become very important in coevolutionary terms, because contrary to the suggestion by Van den Bergh and Stagl (2004: 304) that "biological evolution is generally much slower than cultural, social and economic evolution. As a result, cultural-genetic coevolution is difficult to observe", we find both, (1) cases in which the reciprocal influence of biological evolution on cultural processes is very difficult to see, and (2) occasions in which that influence is explicitly evident, with biological evolution outpacing cultural change. These cases are discussed in the next section.

4.1.3. *Cultural systems and processes*

Once homo sapiens appeared and spread on Earth as a result of natural selection, the development of cultural systems came to produce an interacting complex of social institutions and technologies. From the industrial revolution, the fast development of markets in western (and eastern) economies is literally affecting biological processes and reshaping at great speed the biophysical environment in which they exist. One of the more profound challenges of a coevolutionary theory is to provide a framework from which to study how policies shaping the process of cultural evolution may affect the micro and macro processes of biological evolution, and how these influences may in turn affect current and future cultural systems.

As our previous analysis implies, in both processes of cultural and biological evolution, there are many different units upon which selection forces may act within cultural and biotic systems, respectively, to determine human decisions or adaptation paths.

The first thing to note, however, is that these selection forces act within the particular dynamic conditions of the overall biophysical system. This is precisely the first layer of

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complexity that needs to be clarified. At this very broad level, one should look at how the evolutionary processes going on in cultural and biotic systems affect and are affected by the dynamics of complex biophysical systems, like climate, soils, etc. (all of them regulated by the thermodynamic laws of physics, gravity, solar radiation, and other mechanisms).

In this context, it becomes clear that the dynamic conditions of the biophysical system determine how selection forces operate in the process of biological evolution. On the other hand, the process of cultural evolution — as is also the case for biological evolution — has been, without doubt, actively influenced and shaped by these dynamics; the difference is, however, that the process of cultural evolution, is now literally affecting — accelerating — the dynamics of some of earths' complex systems, in particular, the climatic ones. This, in turn, is affecting both processes, cultural and biological evolution. The process of biological evolution is affected on all fronts, from how variety develops and selection forces operate, to the speed at which ecosystem disturbances take place. All cultural systems are certainly being affected by the changing dynamics of climate, and (western) market economies in particular seem to be in crisis about what to expect or do next (driven by lock-in forces, scientific evidence, money, short-term geopolitical strategies, etc.).

4.2. *Some postulations on coevolutionary theory*

The analysis of the coevolutionary framework developed in preceding paragraphs may offer some interesting general statements or tenets for the development of coevolutionary theory. We find the following:

- The coevolutionary process takes place within the boundaries of embedded systems in our planet as depicted in Fig. 1.
- How these systems affect each other can be (partly) explained by the study of the interlinked/interdependent differential processes to which each system/subsystem is bound.
- The particular relevant units in each evolutionary process can be specified, and their mutual influence depicted. This is done through the study of the determinants of variation and the selection forces that regulate adaptation paths (or learning processes).
- The process of cultural evolution — within a coevolutionary framework — refers to any change in cultural practices as a conscious or unconscious response to the evolution of particular organisms, ecosystems or the overall biophysical system.
- The difficulties of seeing a full (empirically proven) coevolutionary cycle of reciprocal influence between cultural and biological evolution (mostly at the systemic level) should not be enough to disregard the relevance of such a process. In fact, it should be taken as an opportunity for precautionary institutional action in line with what is known, and what can be investigated about more sustainable coevolutionary paths (or coevolutionary development potential).

4.3. *A tentative proposal to structure the study of coevolution*

Once it is understood that the changing dynamics of Earth systems are an intrinsic part of the coevolutionary framework, we can focus on the investigation of the reciprocal influence taking place between cultural and biological evolution. We propose three *coevolution modes* as a way to structure our analysis: (1) Coevolution through systemic influence, (2) Coevolution through direct cultural selection forces, and (3) Forced coevolution through genetic manipulation.

4.3.1. *Coevolution through systemic influence*

This type of coevolution refers to the influence cultural systems exert on the biophysical totality changing some of its dynamics. In turn these changed environmental conditions affect how selection forces operate, and thus, the differential evolution of one or several species (or populations in affected geographic ranges). Finally, the cultural system evolves, responding (or not) to this evolutionary change. While the first and second stages are increasingly being studied and documented, the last step is more difficult to unequivocally determine, since changing institutions, practices or technologies are so far, not aligned with a coevolutionary understanding of progress. Precisely because of this, it is so important to adopt a common coevolutionary theoretical framework for ecological economics, so institutions and technologies can be developed to be consistent with knowledge about the coevolving processes and their consequences on the biophysical systems.

The relevance of the process of cultural evolution is so profound that many biology examples of evolution can be better understood as coevolutionary processes:

> "Pollution of the air, man's first major sacrilege of nature, commenced over 200 years ago. The burning of coal, providing energy for industry, started in several centers in Europe in the second half of the eighteenth century (…). Air pollution has proceeded insidiously since that day and with it the adaptations of living things to the new environment it has created" (Kettlewell, 1973: 54)

Thus, our first example comes from one of the more repeated illustrations in biology textbooks explaining the meaning of evolution (by natural selection). This example comes, among others, from the work of Kettlewell (1973) studying the evolution of cryptic moths — *Biston betularia* — populations in the UK, mediated by a phenomenon he called "industrial melanism". The local effects of the industrial revolution in England in the form of soot and other particles killed off many lichens and darkened tree trunks. Moth populations close to industrial areas that were mostly light, started to change their composition and became mostly dark (a recessive trait up to that moment). The reason was — apparently — natural selection. Since these trunks were the place where moths laid during day hours, and birds feeding on them were the selection forces, the darkened tree trunks provided a differential advantage to dark moths. Finally, in recent years, it seems that more strict clean air standards in the UK could be responsible for the steady fall since the 1970s in the dark moth phenotype frequency in moth populations (Cook, 2003). This example captures the essence of coevolution: first, sociocultural systems developed industries using coal technologies and impacting the biophysical system in unprecedented ways; in turn, this impact changed the conditions under which selection forces operated in the evolutionary process, giving a differential advantage to dark moth phenotypes. Finally, the sociocultural system (institutions) had to respond to increasing environmental and health problems derived from pollution providing, once more, a change in the biophysical conditions that seem to be favouring the recovery of pre-industrial *B. betularia* populations.

At a greater scale, and looking at the potential the process of cultural evolution has to underpin global environmental problems leading to macroevolutionary events, Costanza et al. (2005: 14) suggest that

> "the notion of risk spirals points to a dangerous positive feedback loop. As human societies become more complex, they are less able to withstand shocks from the natural world and, ironically, in the process of making themselves more complex, societies inadvertently and (often) unknowingly change natural systems in ways that make these systems more prone to abrupt changes or extreme events!"

Many global environmental problems fall into this category: acid rain, weakening of the protecting ozone layer, human induced climate change, etc. Inadequate responses to these problems demonstrates the relevance of developing a coevolutionary framework bridging biophysical and social sciences, to provide a more solid and consistent way of confronting and managing complex embedded evolutionary systems. As Mysterud and Penn (2007: 287) point, "conceptual integration refers to the principle that the various disciplines within the behavioural and social sciences should make themselves mutually consistent, and consistent with the natural sciences".

4.3.2. *Coevolution through consciously designed cultural products and processes to act as selection forces in particular coevolutionary events*

The reciprocal changes in the genetic composition of pest populations and in agricultural practices (and technologies), and the possibility to manage this coevolutionary process toward sustainable paths, has been the basis for the development of coevolutionary research focusing on "coevolutionary development potential" (Norgaard, 1984b); "coevolution leading to acceptable biodiversity trajectories" (Conrad and Salas, 1993); or "Healthy coevolution" (Ghersa et al., 1994). In pesticide–pests stories, farmers trying to adapt to economic competitive markets usually change to single crop plantations which become an easy target for pests; in turn, farmers' practices *evolve* using new pesticides that kill most of the pests, but since pests are highly adaptive animals (with relative short reproduction times) respond with increasing immunity, and so on.

The second example refers to a more precise and well studied ongoing coevolutionary process between cultural and biological evolution. This is the case of how the Human Immunodeficiency Virus (HIV) is coevolving with medical practices. Freeman and Herron (2001) use the example of AIDS to illustrate to biology students the process of evolution by natural selection. HIV is a retrovirus that infects human immune system's cells. This infection leads to the collapse of the system and to the condition known as AIDS. The development of drugs to combat the infection was successful at first — AZT therapy — but after only a few years of their use (mid 1990s) patients stop responding to the treatment. What happens is that the virus evolved as a response to drugs (that acted as a selection force on the immune system) by developing AZT-resistant virions. Freeman and Herron (2001: 8) explain this process:

> "HIV has the highest mutation rate of any virus or organism observed to date. Because thousands of generations of HIV replication take place within each patient during the course of an infection, a single strain of HIV can produce hundreds of different reverse transcriptase variants over time. Simply because of their numbers, it is a virtual certainty that one or more of these variants contains amino acid substitution that lessens the reverse transcriptase molecule's affinity for AZT".

As HIV populations became drug resistant, medical practices, now informed of this adaptive capacity, seem to be changing to escape this arm races. This ongoing process is, no doubt, a clear empirically proven example of cultural–biological coevolution. Note that the reciprocal evolutionary loop occurs in two distinct realms: (1) genetic evolution occurring in virus populations within human immune systems as a response to (human designed) drugs and, (2) evolution (cumulative learning) in sociocultural systems (changing drugs and medical practices) adapting to the evolution of the virus.

Extending this example a little more, there are some recent studies showing that HIV could be acting as a "natural" selection force on human populations. This claim is based on the existence of resistant individuals to HIV. It is suggested that some individuals in Caucasian populations may have developed an allele — Δ32 — as a result of the 14th century black plague that now seems to be a protective mechanism against HIV. Consequently, if medical research does not find a way of stopping the virus, natural selection could take place over time favoring the differential reproductive success of individuals carrying the Δ32 allele (Freeman and Herron, 2001).

4.3.3. *Forced coevolution through genetic manipulation*

Through genetic engineering many organism are being adapted to changing conditions, usually aiming at more productive (profitable) purposes. In this case, the cultural system literally becomes the selection force in evolution at the genetic level experimenting with adaptation paths of other species.

A good case of this type of coevolution is provided by Futuyma and Slatkin (1983: 8): "An excellent example of the observation of a direct response to interactions (…) is the appearance of strains of the Hessian fly (Mayetiola destructor) that are able to attack a series of sequentially planted resistant strains of wheat (Gallun, 1977). In this case the wheat 'evolved' according to a controlled plan, rather than as a natural response to the evolution of the fly".

Most of the experimental work with genetic manipulation of crops and other animals happens in a context of uncertainty and, many times, ignorance about its consequences, and new institutional processes are needed to confront this type of bioethical problems (Funtowicz and Ravetz, 1990). This is easily (and worryingly) appreciated by looking at the recent OECD (2006) Safety Assessment of Transgenic Organisms, which details the many uncontrolled aspects of the extensive worldwide use of modified agricultural organisms.

5. Conclusions

One of the most important claims in this article is that the process of cultural evolution affects both the biological processes of microevolution and macroevolution. And it does so, basically in three ways: (1) through large-scale biophysical impacts, (2) through consciously designed cultural products and processes acting as selection forces in particular coevolutionary events and (3) deliberately "manipulating" genetic information. In turn, the process of cultural evolution may be reciprocally affected (and changed) at different levels and intensities by these processes of biological evolution. As we have seen, these may include: large-scale impacts like human induced climate change, affection of biological human evolution (the case of AIDS), or the need to develop knowledgeable and sensible institutions to the coevolutionary process. The relative success of these institutions will depend on many factors at different scales (History, social power structures, short-term economic interests, etc.); however, the development of a proper coevolutionary framework from which to analyse and manage these problems could turn out to be a critical issue for the future of living organisms in our planet.

The main challenge for social sciences is not only to come to grips with the fact that their subject matter is evolutionary; but also, that it is inextricably bound to the evolution of the biophysical system in coevolutionary terms. In particular, there is a need to make evolutionary economics and, in general, other social sciences using metaphoric translations of Darwinism more aware of the non-metaphoric reciprocal influence going on between the processes of biological and cultural evolution and their impact on all earth systems.

Natural and physical sciences need to acknowledge the parallel evolutionary processes driving cultural systems embedded into the biophysical world, and work more closely with social scientist in making progress toward the understanding of the coevolutionary forces shaping our planet.

We still are very much ignorant about the consequences of our actions on the unfolding process of evolution, but much less so than at the beginning of the past century. Complexity, economic and political interests, or overall complacency about the benefits of economic growth should not be used (or allowed) to undermine what we know collectively about the mutual influence of culture and the biophysical environment.

Acknowledgments

This paper was written during a research visit of Miguel A. Gual to the University of California, Berkeley. We would like to thank "Universidad Pablo de Olavide" for funding the visit, Dr. Giorgos Kallis and Prof. Esteban Ruiz for reading the paper and contributing with interesting comments, and finally, many thanks to one anonymous reviewer for a thorough supportive critique on an earlier draft.

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