Ecological Economics 69 (2010) 690–699

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Coevolutionary ecological economics

Giorgos Kallis [a,*], Richard B. Norgaard [b]

[a] ICREA Researcher, ICTA, Universidad Autonoma de Barcelona, ETSE, QC/3095, 08193 Bellatera, Barcelona, Spain
[b] Energy and Resources Group, University of California at Berkeley, 310 Barrows Hall, Berkeley, CA, 94720-3050, United States

ARTICLE INFO

Article history:
Received 28 September 2009
Accepted 28 September 2009
Available online 11 November 2009

Keywords:
Evolution
Coevolution
Socio-ecological systems
Development

ABSTRACT

This paper maps a coevolutionary research agenda for ecological economics. At an epistemological level coevolution offers a powerful logic for transcending environmental and social determinisms and developing a cross-disciplinary approach in the study of socio-ecological systems. We identify four consistent stories emerging out of coevolutionary studies in ecological economics, concerning: environmental degradation and development failure in peripheral regions; the lock-in of unsustainable production–consumption patterns; the vicious cycle between human efforts to control undesirable micro-organisms and the evolution of these organisms; and the adaptive advantages of other-regarding, cooperative behaviors and institutions. We identify challenges in the conceptualization of coevolutionary relationships in relation to: the interaction between different hierarchical levels of evolution; the role of space and social power; uneven rates of change and crises. We conclude with the political implications of a coevolutionary perspective based on the premises of pragmatism.

1. Introduction

Fifteen years passed from the publication of “Development Betrayed” (DB) (Norgaard, 1994). The principal betrayals of development diagnosed in the book — environmental degradation, political deadlock in dealing with it, and intensifying cultural and ethnic hatred — are even more acute today. DB offered coevolution as an alternative framework for “revisioning” development. Coevolution has been recognized as a key framework for understanding change in complex, social–ecological systems (Folke et al., 2005) and as a foundational concept for ecological economics (Gowdy, 1994; Costanza et al., 1997; Spash, 1999). However a coevolutionary research agenda has not taken off within ecological economics (EE). The epistemological and methodological challenges of coevolutionary research are formidable (Norgaard and Kallis, in press). This special section presents a diverse collection of contributions that aim to reinvigorate the coevolutionary analysis of ecological–economic change. This opening article positions these contributions within the growing literature of (co)evolutionary approaches in environmental studies and economics (van den Bergh, 2007; Faber and Frenken, 2009; various contributors in Rammel et al., 2007). Our ambition is to map a tentative coevolutionary research agenda for EE.

Let us start with a basic definition of evolution and coevolution. Evolution is a process of selective retention of renewable variation (Campbell, 1969; Nelson, 1995). It applies to complex populations of entities that are similar in key respects, but within each type there is some degree of variation (Hodgson, 2010-this issue). Evolution involves the three Darwinian processes of variation, inheritance, and selection. An evolutionary analysis explains how variety is generated (renewed) in the population, how advantageous properties are retained and passed on and why entities differ in their propagation (Hodgson, 2010-this issue; Nelson, 1995). Evolving entities might include organisms in the biological world, or organizations, institutions and technologies in the social world. Units of selection might include genes, habits, norms, strategies or behaviors (Kallis, 2007a). Although evolution in biological and social systems may exhibit the same three Darwinian processes, they also differ in significant ways. In social systems the generation of variation is sometimes partly guided, while in biological systems it is accidental through mutations (Warring, 2010-this issue; Aldrich, 1999; Boyd and Richerson, 1985).

Two systems coevolve when they both evolve in the above indicated sense and they have a causal influence on each other's evolution (Kallis, 2007a).[1] Interacting systems might be biological, social or both. Coevolution is different than mere co-dynamic change although they are often misused synonymously (van den Bergh and Stagl, 2003; Winder et al., 2005). The difference in coevolution is that at least one — social or environmental — system is evolving, i.e. changing through variation, selection and inheritance. Also coevolution is not a normative concept; it is emphatically not about social

* Corresponding author. Tel.: +34 93 581 3749.
E-mail address: Giorgoskallis@gmail.com (G. Kallis).

[1] The range of coevolutionary phenomena can be expanded by relaxing the condition of reciprocity (i.e. only one system affects the evolution of the other) or by accepting as sufficient that at least one (and not necessarily) all of the interacting systems are evolving.

0921-8009/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolecon.2009.09.017

systems changing in harmony with nature as Thiele (1999) or Conrad and Salas (1993), mean it. Coevolutionary relationships can be mutually cooperative, but also competitive parasitic, predatory or dominative. Coevolution is a value-free process of change (Norgaard, 1994). Norgaard (1984) proposes instead to use the term coevolutionary development for coevolution between society and nature that is valued as beneficial by humans.

Coevolution is all-pervasive. For example, as the environment of one species consists of multiple other species, coevolutionary relations characterize almost all of what normally passes as evolution in biology. Biologists find useful methodologically the distinction between "direct" — clearly defined and documented, species-to-species — coevolution and more widespread, "diffuse" coevolution (Futuyma and Slatkin, 1983). Many of the systems that matter in the social and natural worlds, such as institutions, technologies, beliefs, values, genes, human and animal behaviors, are evolving diffusedly affecting the evolution of each other (Norgaard, 1994). Rather than debating whether a focus on direct or diffuse coevolution makes more sense for EE (see debate between Winder et al. (2005), Norgaard (2005), and Winder (2005)), a more productive approach is to recognize that each has something to offer (Kallis, 2007b). A generalized "coevolutionary logic" (Porter, 2006) of diffused evolving interdependence offers a good basis for a new epistemology or "cosmology" as Norgaard (1994) put it. On the other hand for formal theorizing (Nelson, 1995) and the development of an empirical research program focus has to shift to direct "coevolutionary mechanisms" (Porter, 2006). An understanding that "everything" might be coevolving with everything else needs to be complemented with the identification of what is coevolving with what and how in specific conditions or contexts and as relevant to specific analytical and policy purposes (Malerba, 2006; Kallis, 2007b; Norgaard and Kallis, in press).

The next two sections revisit the material of DB under this perspective. Section 2 clarifies the different types of coevolutionary mechanisms that are relevant for empirical EE research. Section 3 shows how these mechanisms put together suggest a broader coevolutionary logic, and illustrates the power of this logic to transcend mal-adaptive epistemological dichotomies that confound EE and environmental studies in general. Section 4 synthesizes recent coevolutionary contributions, including those in this special section, into four key theses. Each of these relies on an eclectic combination of coevolution with other theories and analytical tools, as relevant to the specific application and domain of study. Section 5 identifies challenging research questions in coevolutionary studies. Section 6 engages with broader normative and epistemological issues and concludes with the contribution of coevolution to policy.

2. Coevolutionary mechanisms

Here we offer a conceptual breakdown of five types of coevolution that are important for EE (see also van den Bergh and Stagl, 2003; Gual and Norgaard, 2010-this issue). In a different work we discuss in detail the unavoidable tensions between any such reducing categorization and the broader coevolutionary logic which suggests a more widespread coevolution between all the systems described below (Norgaard and Kallis, in press).

2.1. Biological coevolution

This refers to reciprocal evolution between two or more interacting species (Ehrlich and Raven, 1964; Thompson, 2005). Examples abound: the evolution of the beaks of hummingbirds and the shape of the flowers they feed on, the behavior of bees and the distribution of flowering plants, the biochemical defenses of plants and the immunity of their insect prey, or "tri-partite" relations, such as those between nutcracker birds, pine trees and squirrels (Ehrlich and Raven, 1964; Thompson, 2005; Pennisi, 2007). Coevolutionary interactions, intensities and rates between the same species vary depending on ecological settings. Thompson (2005) calls such variations "geographic mosaics".

Interest on biological coevolution has surged because of its importance for sound conservation policies. Coevolution sheds light on keystone species or the impacts from the reintroduction or invasion of new species in ecosystems (Pennisi, 2007). Ecological–economic models dealing with biodiversity should take biological coevolution into account. Furthermore, equilibrium concepts, such as the "marginal value" of species, are inappropriate in coevolutionary settings. Temporally and spatially varying interactions mean that the ecological value of species varies geographically. Extinction of keystone species has far reaching evolutionary effects and cannot be valued like any other species (van den Bergh and Gowdy, 2000).

2.2. Social coevolution

This includes reciprocal evolution of two or more social systems. Here too possibilities abound and include — among others — coevolution of technologies and institutions (Nelson, 2002), populations of industries and universities (Murmann, 2003), behaviors and institutions (van den Bergh and Stagl, 2003), populations of producers and consumers, or supply–demand coevolution (Safarzynska and van den Bergh, in press; Janssen and Jager, 2008; Saint Jean, 2005; Windrum et al., 2009), organizations and their environments (Porter, 2006; McKelvey, 1982; Baum and Singh, 1994; Lewin and Volberda, 1999), political strategies and technological paradigms (Ward, 2003), or perceptions and actions (Weick, 1979). Applications relevant to environmental policy abound. Social evolution and coevolution can be employed to shed light on the emergence and performance of environmental institutions (Hodgson, 2010-this issue), lock-in barriers and transition policies for the adoption of environmental technologies (Safarzynska and van den Bergh, in press; van den Bergh, 2007; Faber and Frenken, 2009) or the potential evolution of greener corporations (Porter, 2006).

2.3. Gene–culture coevolution

This refers to interactions between cultural evolution[2] and biological evolution of the human species (Durham, 1991). Warring (2010-this issue) lists several examples such as the coevolution of sign language with deafness, lactose-tolerance with dairy farming, incest taboos with brother–sister mating or sickle-cell anemia with forest clearing practices (see also Durham, 1991; Laland and Boogert, 2010-this issue). Crucially, the human mind, cognition and perception seem to have evolved influenced by the cultural context (language, use of tools, etc) (Deacon, 1997; Dunbar, 1993; Laland and Boogert, 2010-this issue).

Gene–culture coevolution and dual genetic–cultural inheritance theories imply that human behavior is not solely biologically determined; endogenous cultural dynamics should be accounted for (Warring, 2010-this issue). Cultural learning, imitation and experimentation shape human behaviors; they are conditioned by human biology, and in turn change it (Norgaard, 1994). Neo-classical economics' behavioral assumptions of genetically-determined, selfish maximizers are unrealistic (Manner and Gowdy, 2010-this issue; Warring, 2010-this issue). Bounded rationality, routinised behavior and choice through heuristics may offer better behavioral foundations for EE (van den Bergh et al., 2006).

[2] Culture might be considered as a subset of the social world, and cultural evolution as a particular case of social evolution. Durham (1990) limits the definition of culture to ideational phenomena and includes in his definition only values, ideas and beliefs that guide human behavior and not the behavior itself. Cultural anthropologists and ecologists often focus on non-Western, subsistence societies; by default sometimes cultural evolution is used to denote evolution of habits or artifacts in such "primitive" societies, compared to "social evolution" of technologies, laws or organizational forms in "advanced" contemporary societies.

2.4. Bio-social coevolution

This refers to reciprocal influences between social evolution and non-human biological evolution. Examples include coevolution between pest populations and economic strategies or regulatory policies for the pesticide industry (Norgaard, 1994; Noailly, 2008), fishing practices and fish populations (Noailly et al., 2003; Heino, 1997) or viruses and medical practices (Laxnminarayan, 2001; Gual and Norgaard, 2010-this issue).

A distinction should be made between the above examples and human-induced bio-social coevolution, where humans intentionally manipulate genetically biological populations through artificial selection (i.e. selective breeding) or genetic engineering (Gual and Norgaard, 2010-this issue). An example of human induced coevolution is the domestication of animals, e.g. wolves to dogs, or food crops which in turn had selective influences on cultural practices and social institutions. Progress in understanding and manipulating human and other species' genome moves the human influence on evolution to another dimension. Human controlled evolution and coevolution might dominate natural coevolution, especially in the short term (Gual and Norgaard, 2010-this issue).

2.5. Socio-ecological coevolution

This refers to cases where evolution in the social system affects the bio-physical environment, which in turn affects evolution in the social system (Norgaard, 1994). For example evolution of water technologies and consumptive practices spurred the transformation of rivers into dammed reservoirs; in turn the availability of abundant water supplies from dams selected for new water supply technologies and more consumptive water behaviors and practices (Kallis, 2010-this issue). A similar coevolution takes place between the development of fossil fuel resources, power generation systems and energy-intensive cultural habits (Unruh, 2000; Norgaard, 1994).

In this conceptualization, the bio-physical system is not evolving literally, as in bio-social coevolution, but manipulated through evolving changes in the social system. In turn, positive feedbacks from the transformed biophysical system affect the evolution of social subsystems (Norgaard, 1994). This is somewhat analogous to the process described by biologists as niche construction (Laland and Boogert, 2010-this issue), a "process whereby organisms, through their metabolism, their activities their choices, modify their own and/or each others' niches" (Odling-Smee et al., 2003, p.419).[3] Niche construction is an important force in all types of coevolution, biological, gene–culture, bio-social, social and socio-ecological. An example in the biological sphere are the beavers who when they build dams they change the habitat and modify the pattern and strength of selection acting on a host of beaver genetic traits and on thousand of other species (Laland and Boogert, 2010-this issue). Cultural niche construction is an important force also of gene–culture interactions such as forest clearing practices related to the evolution of sickle-cell anemia (Laland et al., 2001). Socio-ecological coevolution involves a social niche construction; there is nothing fundamentally different between beavers and humans constructing water dams which in turn affect the evolution of various social subsystems such as water technologies, water institutions or consumption habits (Kallis, 2010-this issue).

3. Coevolutionary logic and epistemology

Replacing "ors" with "ands" coevolution has facilitated connecting different disciplines such as ecology and biology (biological coevolution), anthropology and biology (gene–culture coevolution), sociology, political science and economics (social coevolution) or ecology and economics (biosocial and socio-ecological coevolution). "Development Betrayed" went one step further suggesting a broader coevolutionary logic, whereby multiple sub-components such as genes, minds, perceptions, behaviors, actions, institutions, technologies, environments, also coevolve and interact. Schematically this was depicted in a coevolutionary pentagon (Fig. 1), though the possibilities of coevolving factors can be expanded to include many others (Norgaard, 2005). In effect Fig. 1 brings together the five types of coevolution (Section 2) into a grand, master framework.

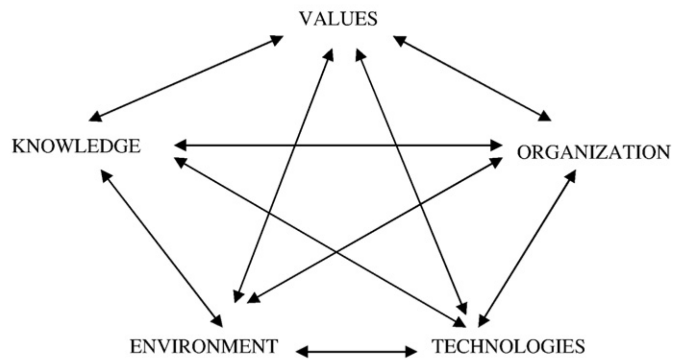

Fig. 1. The coevolutionary process (Norgaard, 1994).

Epistemologically this logic offers entry-points to transcend dichotomous debates that confound EE and environmental studies. For example much discussion has gone on the extent to which human nature can be molded culturally; this relates to the so called nature vs. nurture debate. Another hot topic is whether biophysical environments limit and condition decisively human societies or whether societies can overcome limits and mold environments to their desires; the so called nature vs. culture or limits to growth debates. Environmental sociology is also torn between those who ascribe primacy to the material reality and biophysical causes of environmental problems and those who argue that nature is a social construction, our perceptions determining what counts as an environmental problem and what not (Woodgate and Redcclift, 1998). Coevolution can in theory overcome such dualisms by proposing that genes coevolve with culture, societies with ecosystems and perceptions with actions (Norgaard, 1994; Kallis, 2007b). We might be limited by our genes and our biophysical environment, but in turn we have historically superseded and conditioned the biological features of ours' and other species and the physical environments we live in (Gual and Norgaard, 2010-this issue).

Importantly, evolutionary and coevolutionary thinking offer a conceptual way out of a key issue in the social sciences, this of agency vs. structure, i.e. "how much scope do people have for independence and creativity in the face of social structural constraints on their understanding and behavior" (Aldrich, 1999, 23). An evolutionary perspective separates the issue of the conditions under which variations are produced from the issue of the conditions under which they are selectively retained. The diffusion of a particular behavior or practice is determined by its consequences, which may well have been unforeseen or even unknown before the practice took place (Aldrich, 1999, 23). Evolution marries agency in experimentation with structure in selection (Norgaard, 1994; Kerr, 2002).

It is difficult, if not impossible to relate the aforementioned broad coevolutionary logic to specific empirical cases (Norgaard and Kallis, in press). A more viable research strategy is, with this framework in the background, to derive problem-specific hypotheses, combining one or more coevolutionary mechanisms with insights from other theories. In DB for example, Norgaard (1994) combined insights from coevolutionary and other theories to develop a broader (hypo)thesis

[3] Lewontin (2000) referred to in the past to niche construction as organism–environment coevolution.

The thesis: *With industrialization social systems stopped responding and adapting to the feedbacks of their local environments. They coevolved and adapted at a larger scale to the availability of fossil fuels. Technologies, institutions, knowledge, values, preferences and behaviors mutually adapted and reinforced one another, while coevolving with the environments produced by the exploitation of low entropy. Relatively efficient agricultural (subsistence) systems that secured basic value surplus for local populations gave their place to industrialized market systems. These may appear as producing higher surpluses but in fact hide spatial and generational cost transfers and increased bureaucratic (transaction) costs. As society evolves in lockstep with fossil fuels, the risks from their eventual exhaustion are increasing. Path-dependencies and lock-in of technologies, institutions, ideas and resource systems make it hard to change course.*

Inter-disciplinary field	Coevolutionary and other theoretical concepts	Key exponents
Cultural Ecology	- Evolutionary adaptation of subsistence communities through experimentation and trial and error to ecosystem conditions (socio-ecological coevolution). - Subsistence economies can have a higher energy efficiency than developed market economies.	Julian Steward Robert Netting
Evolutionary Anthropology Evolutionary Cultural Theory	- Learning shapes human behavior (gene-culture coevolution, dual inheritance). - Cultural evolution of preferences.	William Durham Boyd and Richerson
Organizational Psychology	- People discover and modify their preferences as they interact and as they reflect on the results of their actions (social coevolution).	Karl Weick
Evolutionary Economics	- Institutions and technologies evolve through experimentation and selection and affect one another (social coevolution).	Nelson and Winter Keneth Boulding
Ecological Economics	- Positive feedbacks between social and environmental systems. - Substitution of ecosystem services by economic processes. - Focus on surplus value (costs and benefits) of environmental change, accounting for transaction costs, non-monetary values and intergroup and intertemporal transfers. - Increasing reliance of modern economies on the exploitation of low entropy sources stocks.	Herman Daly Nicholas Georgescu-Roegen

Fig. 2. The Development Betrayed thesis and its intellectual roots. (Steward, 1972; Netting, 1986; Durham, 1991; Boyd and Richerson, 1985; Weick, 1979; Nelson and Winter, 1982; Boulding, 1978; Daly, 1977; Georgescu-Roegen, 1971).

about the failure of development (Fig. 2). In turn, the (hypo)theses derived from this theory were applied to show how and why development programs failed in the Brazilian Amazon (Norgaard, 1981, 1994).

As Hodgson (2010-this issue) notes "applied biologists are not obliged to refer to general Darwinian evolutionary principles when they carry out concrete studies. Much of biology proceeds by assuming but not mentioning the core Darwinian principles of variation, inheritance and selection…Middle-range theory has to be consistent with this theory but it does not necessarily involve applying it at every turn". Along these lines, we argue that coevolutionary studies in EE should make proper use of the term coevolution (van den Bergh and Stagl, 2003, Winder et al., 2005), but they do not have to be constrained to "proving" coevolution at every turn, documenting empirically populations and measuring changing frequency of attributes, as Winder et al (2005) seem to suggest. Indeed there are very few empirical studies of population changes in the social sciences (see Aldrich, 1999 for a review of the literature in organization studies and van den Heuvel and van den Bergh, 2008 for a rare environmental application). While population demographics of evolving ecological and economic systems might be an interesting research endeavor, there is also a lot to learn from middle-range theory benefiting from a coevolutionary understanding. And indeed this is what coevolutionary studies have been doing to date (Kallis, 2007a). Looking at what people who claim that they do coevolution actually do, we see some emerging patterns in the issues, questions, and narratives (theses) studied. We codify these into four cross-cutting themes.

4. Coevolutionary studies and theses

4.1. Development betrayals

The transformation and degradation of innocuous local resource systems in peripheral — rural and developing world — regions as they enter global export markets is a theme well-studied by cultural and political ecology. It featured strongly in Norgaard's (1981) early work on the Amazon. The key thesis here is that the institutions and practices (technologies) of many local communities at the fringes of the market economy are often well adapted to their ecological settings, yielding basic subsistence surpluses. This is the result of a historical evolutionary adaptation to ecosystem features through trial and error experimentation, cultural learning and inheritance of successful innovations. The arrival of "development" (government policies and infrastructures, export-oriented activities and trade in global markets) widens coevolutionary processes from interactions with local ecosystems to regional and global influences (e.g. fossil fuels and global markets), reducing local autonomy and increasing vulnerability. Often, productive practices which are mal-adapted to the particularities of local ecosystems are introduced in the name of development. The sociosystem fails to substitute the regulatory mechanisms and services of the ecosystems, and the local environment degrades, while development fails (Norgaard, 1994; Dove, 1993). Saifi and Drake (2008) analyze coevolutionary processes in the context of agriculture arguing that rural sustainability requires reducing interaction and interconnectedness with higher levels especially on material flows, re-establishing local coevolutionary feedbacks (see also Dove, 1993; Norgaard, 1984).

With their contribution in this special section, Moreno-Peñaranda and Kallis add some nuance to this narrative. Following the history of an isolated rural community in southern Brazil, they show how external introductions are not mal-adaptive *per se*, but reconfigure and transform the local selection environment for good and for bad, in turn creating new evolutionary possibilities. Rather than a strict normative distinction between global mal-adaptive and local well-adapted practices, Moreno-Peñaranda and Kallis (2010-this issue) find that the most important trait is production diversity, both at the level of individual households and the community as a whole. The rural households studied appropriated exogenous production opportunities while maintaining a diverse farm structure that they inherited from indigenous groups. However, the diminishing isolation of the community and its increasing integration to regional and global markets the last years seems to intensify selective pressures and reduce diversity.

4.2. Unsustainable lock-ins

A key question in environmental studies concerns the failure to adopt greener technologies such as renewable energies, water efficient appliances or pesticide-free production, even when such technologies are superior to existing variants (Unruh, 2000; Cowan and Gunby, 1996). According to the path-dependence and lock-in thesis, a technological variant that for some reason — historical or mere luck — gains an early lead from competitors and captures a critical mass of the market early on in the development of a technology, may become the de facto standard and dominate the population of designs, locking-out alternatives as increasing returns amplify the initial lead (Arthur, 1989). Increasing returns stem from scale economies, learning economies, adaptive expectations and systemic network effects (Arthur, 1989). A similar pattern of historical lock-in through increasing returns is observed in institutional evolution (Mahoney, 2000), including environmental institutions such as water policies (Ingram and Fraser, 2006).

There is a proliferation of studies of the dynamics of technological lock-in with multi-agent simulation models of the coevolution of heterogeneous populations of producers and consumers (Janssen and Jager, 2008; Saint Jean, 2005; Windrum et al., 2009). A shared conclusion concerns the importance of policy measures and regulations that let environmental technologies mature in protected niche markets before introduced in the mass markets (Faber and Frenken, 2009). A recent model by Safarzynska and van den Bergh (in press) is the first that studies increasing returns on both the producers' and consumers' sides (in the latter through conformity, positional goods and market share) as well as interactions between supply and demand through prices, advertising and other effects. Evaluating four policy transition alternatives, namely a monopoly tax, a public campaign, a preferential tax for new firms and a subsidy for quality improvements and advertising, the study finds that results are very sensitive to the specification of the demand side, in particular whether consumers evaluate attractiveness of products on the basis of market shares or inter-social comparison (public campaigns for example are more effective in the second case).

Such supply–demand coevolution studies treat policies as exogenous. However there are also studies which focus particularly on policy evolution and coevolution between different components of the policy system (Kerr, 2002; Ward, 2003) or institutional path-dependence and lock-in (Mahoney, 2000; Pierson, 2000). A few studies also address the coevolution between technologies and institutions, focusing not on single technologies and products but on the mutual adaptation of technological and policy paradigms (Nelson, 2002; Frenken, 2000, Ward, 2003).

All these studies concern "social coevolution" according to the terminology of Section 2. None explicitly addresses the role of resource and biophysical systems in techno-institutional coevolution (Gual and Norgaard, 2010-this issue). Environmental technologies are treated in essence as any other technology entering a market dominated by a historically entrenched product. Environmental factors however might affect the competition of technologies; land, energy or water resources are dominated by diminishing returns that confound lock-in as recognized by Arthur (1989). Complicated dynamics might result from increasing market or institutional returns and decreasing resource returns. Environmental degradation and resource exhaustion might create favorable environments for the evolution of alternative technologies and institutions (Cowan and Gunby, 1996).

Also whereas supply–demand studies understand the supply side as a competitive market of alternative products, the coevolution of production and consumption is often driven by collective infrastructures of water, energy, power generation or transport where variation and competition are minimal. Kallis (2010-this issue) offers an appreciative account (c.f. the "formal models" reviewed above)[4] of urban water infrastructure development as a coevolution between the cultural water practices of a heterogeneous population of households, a policy system consisting of competing policy solutions for providing water and a hydrological environment transformed by these policies. Following the history of water and urbanization in Athens, Greece he shows how positive feedbacks between evolving supply and demand have locked in the system in a trajectory of continuous expansion at the expense of environment and the countryside. Treating policy as an endogenous factor, this analysis does not focus on policies for transitions, but rather on social–political dynamics and the opportunities that changing hydro-environmental conditions offer to social movements who support policy alternatives, such as water conservation, to stop supply expansion.

4.3. Bio-environmental problems and the micro-world

Interactions between social systems and the genetic evolution of other species, including animal species and micro-species such as viruses, bacteria and pests appear central in public health problems including the spread of viruses like HIV, the crossing of diseases from animals to humans or the chemical contamination of food (see discussion in Gual and Norgaard, 2010-this issue). Such problems may get worse as humans gain increasing power to intervene deliberately in the genetic evolution of other species.

Hird (2010-this issue) underscores the vital role of bacteria in the making of the biological and the human world. The human body hosts a biodiverse flora of hundreds of species of bacteria, some harmless, other beneficial and other deadly. Symbiogenetic evolution — the generation of new organs, tissues and species through symbiotic mergers — may be a more important force of evolution than the

[4] In the "appreciative" mode, theory is put in general terms and provides a framework to organize analysis. "Formal" theory is more abstract and includes an explicit set of causal propositions in mathematical or verbal form. In practice of course theorists often mix appreciative with formal theorizing, formalize appreciative theory in models or use appreciative accounts to discuss the implications of formal models (Nelson, 1995).

accumulation and selection of mutations (Margulis, 1981; Hird, 2010-this issue). Hird reminds us that bacteria exceed in numbers all other forms of life and entertains the idea that rather than us humans selecting plants and other forms of life, it is bacteria that are the selecting modes of human cultural and social selection that enhance bacterial survival. European colonization of the Americas, she argues, was driven as much by bacteria as by humans.

Our understanding of the complex interaction between human practices and institutions (e.g. medical or farming practices), bacterial and other microorganism species in our bodies, animals and the species they carry are very preliminary, pointing to an important research agenda where social scientists, including ecological economists, and biologists need to join forces. Coevolutionary studies narrate a pattern of vicious cycles and coevolutionary arm races of intervention — resistance, such as between pests and pesticides or viruses and drugs, with detrimental public health impacts. Noailly (2008) is the first to model interactions between a heterogeneous population of farmers (classified in terms of those adopting an "intensive" and those adopting a "biological" strategy) and a genetically diverse population of pests (in terms of resistance). Norgaard (1994) opened this line of thinking with an appreciative theory of the coevolution between pesticide regulation, the pest industry and pests on the ground.

4.4. Other-regarding behavior and cooperation

Economics, as well as much of biology and sociobiology, have traditionally treated other-regarding behavior and cooperation as rare, exceptional results that need to be explained in each case they surface (Worden, 2010-this issue). Free-ridding behavior and the tragedy of the commons are seen as dominant tendencies in biological and social systems and collective cooperation the exception. Yet a new ensemble of concepts, models, experiments and empirical studies from biology, game theory and anthropology make a strong case that, as Gintis and Bowles put it in the title of their forthcoming book, "humans are a cooperative species" (see also Bowles and Gintis, 2008). Other-regarding behavior often trumps selfishness (Warring, 2010-this issue; Manner and Gowdy, 2010-this issue).

Multi-level selection and coevolutionary models contribute to this thesis (Warring, 2010-this issue). Natural selection can operate simultaneously at different levels of the biological hierarchy from genes, to groups, species, communities or even ecosystems (Okasha, 2003; Worden, 2010-this issue). Lower-level selection may favor selfish behavior. However selection on the higher levels will tend to favor other-regarding behavior and cooperation at the lower levels. Manner and Gowdy (2010-this issue) combine insights from the Price equation from evolutionary biology and other empirical findings from biology, neuroscience, animal studies and anthropology, to argue that other-regarding behavior is likely to emerge over time as cultural group selection benefits group-beneficial attributes over individually-beneficial — but group maladaptive — attributes. Neuroscience confirms the expectations that through gene–culture coevolution, sociality traits such as empathy, love and altruism have been hard-wired genetically in the human brain (Manner and Gowdy, 2010-this issue). Such a hierarchical understanding not only dispels the myth of an unequivocally selfish human nature that underpins much of modern economics, but also challenges the Alchian (1950) proposition that even if economic agents were not by their biological nature selfish, they would sooner or later become as markets select for selfish maximizers. Multi-level social selection suggests that under certain conditions social groups (firms, industries, and countries) where selfish behavior dominates at the expense of the group, they may perish together with the individuals and behaviors that comprise them.

In his contribution to this section, Worden (2010-this issue) shows how cooperation between species might emerge even at the ultimate level of the biosphere as a whole, despite the "population of one" problem, i.e. the fact that the biosphere is not part of a population of similar entities that would favor cooperation at lower levels. Sequential selection is a process in which inviable community structures give their place to viable ones by a sequence of restructuring. Ecological communities in Worden's model are stabilized by feedback processes in which global atmospheric temperature is an essential component. When a community of species loses control of its environment, it comes to a crisis, which forces extinctions or other kinds of structural shift, after which the community may or may not be self-regulating. This process can repeat sequentially, but it can only result in a Gaian community or in total extinction (Worden, 2010-this issue). Worden urges caution with assuming tragic scenarios; these result from perverse incentive structures, but perversity cannot be assumed, it should be documented. In his models, sequential selection favors in the long-term communities without perverse incentive structures as those with perverse structures go extinct.

To put it simply, what such multi-level, coevolutionary models suggest is that communities that do not manage to deal with selfish free-riders and avert the tragedy of the commons through cooperative behavior and proper incentive structures are likely to be weeded out in the long-term by group or sequential selection. This theoretical expectation fits well empirical observation. Cooperative, self-organizing institutions that manage the commons effectively are indeed common (Ostrom, 1990).

The fact that humans are not only selfish does not mean that they are never selfish. Humans have multiple genetic and behavioral possibilities. The debate whether humans are selfish or cooperative is misleading; they are of course both, but different possibilities are privileged in different contexts, or under different "incentive structures" as Worden puts it. Models, games and simulations, like the prisoners' dilemma or the tragedy of the commons say as much about the possibilities of human nature as they say about the institutional (relational) and resource contexts within which their agents are put to operate. In this sense, it is important to develop further coevolutionary modeling and simulation work along the lines pursued by Manner and Gowdy or Worden to understand better the interplay between human behaviors, institutional incentives and resource (ecosystem) dynamics and therefore the conditions under which cooperative norms and institutions are likely to emerge.

In addition to such theoretical work, it is important to observe actual behaviors, norms and institutions in the real-world and understand empirically the factors that affect them. Brooks (2010-this issue) contributes to this research agenda with a survey of a population of mushroom harvesters in Bhutan and an analysis of the factors that associate with conservation behavior. Income, education and perception of resource scarcity correlate positively with conservation behavior, though there are differences between punisher–conservators and cooperators, i.e. those that voluntarily forego harvesting. Brooks predicts an evolution of conservation norms, both punishing and cooperating, and an emergence of related institutions as resource scarcity intensifies and harvesters learn about it. Mushroom harvesting is a relatively new economic activity in Bhutan and the evolution of the harvesting community is at its early stages; it remains to be seen whether it will go extinct or survive through developing cooperative norms and institutions.

4.5. Future research

Table 1 summarizes the four main areas where coevolutionary studies are making a contribution and have much to offer in the future.

In each of the four themes there is scope for both formal coevolutionary models (like Safarzynka and van den Bergh, in press or Worden, 2010-this issue) and for appreciative empirical accounts like those offered by Norgaard (1981) or Kallis (2010-this issue) and

Table 1
Four themes for coevolutionary research.

Theme	Coevolution types involved	Related (sub)disciplines	Policy relevance
Development betrayals	Social Socio-ecological	Cultural ecology Political ecology Development studies	Regional/local environmental degradation Design of development policies
Unsustainable lock-ins	Social Socio-ecological	Technological studies and evolutionary economics Historical sociology — institutional economics	Barriers to adoption of greener technologies Barriers to institutional reform Design of transition policies
Bio-environmental problems	Bio-social Social Socio-ecological	Biology Microbiology — immunology Agricultural/animal studies	Diseases and Public Health Food security
Cooperation and other-regarding behavior	Biological Gene–culture Social	(Theoretical) biology Sociobiology Anthropology Game theory	Evolution of cooperative norms and institutions to manage the commons

Moreno-Peñaranda and Kallis (2010-this issue). In the next section we discuss some issues that confound both the formal modeling and appreciative coevolutionary analysis.

5. Open questions

5.1. Levels of coevolution

Evolution takes place at different levels of nested biological and social hierarchies. In biology evolution may involve selection at the level of genes, groups, species, or more disputably, communities and ecosystems (Okasha, 2003). In economic evolution there might be selection within firms, i.e. internal selection of competing management routines, selection of individual firms at the level of the industry, selection of agglomeration of firms (industries) at the level of domestic and international markets, or selection of whole national or regional economies and economic systems (Nelson, 1995). Evolution at lower levels of a hierarchy is obviously affected by evolution at higher levels, as in group selection in biology. The specification of the relative contributions to change of different levels of evolution within a hierarchical system poses a challenge. Biologists debate hotly the relative importance of genes vs. groups in biological evolution. Philosophers of evolution are divided between realists, who maintain that there is always a fact of the matter about the level or levels of selection operating in a different scenario and pluralists who hold that there is often not such a fact and that we are faced with a choice of perspective (Okasha, 2003).

Complicating matters even further, there might be interactions and coevolution between the different levels of the hierarchy, as in gene–cultural interactions in biological hierarchies (Durham, 1991), or firm–industry coevolution in economic hierarchies (Lewin and Volberda, 1999). Complexity explodes as coevolution within hierarchical systems (i.e. among interacting hierarchical levels) combines with coevolution between different biological and social hierarchical systems. Such relationships between multi-level evolution and coevolution has not been adequately conceptualized, modeled or studied empirically. The conceptual challenge is how to frame the different levels of evolution in social systems and their internal and external interactions, especially with multi-leveled biophysical systems. Intensities of interaction between different levels of the same hierarchy may not be symmetrical, complicated by the fact that higher levels represent aggregations of lower levels. Scale mismatches between different interacting systems also complicate the specification of coevolution; for example resistant pests may evolve on specific, geographically bounded areas, whereas policies or knowledge about the problem operate at completely different scales such as the institutional arenas of the European Union. Future coevolutionary ecological–economic models and empirical analyses should embrace this complexity and specify more precisely the different levels of (co) evolution, within and between hierarchies, their weights, and the nature of their interactions.

5.2. Boundaries and geography

Spatial isolation is a main mechanism of speciation and biological evolution (Mayr, 2001). Comparative studies of coevolutionary interactions in different geographical settings are central in biology (Thompson, 2005). “Geography matters” in socio-ecological coevolution too as “the emergence of complex structures requires the friction of distance or the shelter of boundaries” (Clark and Tsai, 2002, 426). Moreno-Peñaranda and Kallis (2010-this issue) studying the economic evolution of a rural community in Brazil note the crucial role of changing time–distance between the community and regional centres or global markets, but leave for future research the conceptualization of space, boundaries and isolation in coevolutionary dynamics. Similarly the studies of supply–demand coevolution reviewed in Section 4, are performed either at an abstract — non-spatial level, or applied empirically to bounded areas, such as national industries and markets or cities. This lack of attention to space or comparative coevolutionary trajectories in different areas is all the more conspicuous, given the central role of isolation in the creation of niches for new technologies. Space and isolation remain under-theorized in coevolutionary studies (but see Boschma and Martin, 2007).

Vice versa, the question is why very similar coevolutionary interactions and patterns of lock-in are observed in very different geographical settings. From evolutionary theory we would expect a higher degree of diversity, e.g. in modes of producing water or energy, than currently experienced. We may hypothesize that there is a link between globalization, “the annihilation of space by time” as famously called by Marx, and a reduction of cultural and ecological diversity at a global level (Norgaard, 1994). There is a need to study “coevolution under globalization” (Clark and Tsai, 2002) and not only in abstract or within artificially established analytical borders.

5.3. Power and inequalities

While inequalities and power issues featured strongly in DB, they were not integrated in the conceptual coevolutionary model, framed as it was at a general systems level, which did not address relations between human agents (McGlade et al., 2006; Norgaard, 2005). Coevolutionary change, as any other change, is prone to create or redistribute inequalities. In turn, inequalities in social and economic power are a constitutive part of coevolutionary change. Power and inequality remain undertheorized in evolutionary economics too, despite the fact that social power has a central role in technological and institutional change, and income inequalities affect the market selection of new products (Vona and Patriarca, 2009).

One general, but rather underspecified way to conceptualize power is as a selection force that affects the relative survival of social variants, such as technologies, ideas or policies (Nelson, 1995, see also Kallis, 2010-this issue). Worden (2010-this issue) sees patterns in his model of ecological communities — atmosphere dynamics that resemble notions of structural power in the social sciences. These include the special positioning of some players (species) in the ecological networks in ways that give them the ability to determine system outcomes and induce others to act in certain ways (alike keystone species in ecosystems), and the development of bilateral coevolutionary relationships between parties that manage to control the global environment for their benefit, while those that cannot keep up go extinct. Safarzynska and van den Bergh (2010-this issue) offer a much needed review and classification of theories of power in economics and the social sciences and explore potential ways in which power can be conceptualized and modeled within multi-level selection dynamics. Currently there is no formal model or empirical coevolutionary work that takes into account power relationships and this is a priority research topic for the future.

5.4. Rates of change and crises

Rates of change of interacting evolutionary systems may be mismatched, as for example the evolution of pests and the evolution of regulatory policies that deal with pesticides. Evolutionary change may also not be even; it can exhibit different rates at different points in time. Political scientists for example, have documented the U-shape of political evolution over time, large periods of inaction followed by crises, intense searches for innovation and struggle between competing ideas (Baumgartner and Jones, 1993; Kerr, 2002; Kallis, 2010-this issue). In political change analogies have been invoked with the idea of punctuated equilibrium in macro-evolution (Gould, 2002). As coevolving systems may change in different and altering rates, mutual selection may not be synchronic and the intensity and nature of interaction vary over time. Both social and ecological systems exhibit often tipping points and thresholds beyond which change precipitates.

Biologist Stephen Gould (2002) has argued about the importance of large-scale, systemic environmental changes in evolution. To put it simply, humans did not outcompete the dinosaurs. Big events, or shocks, may change the course of evolution, even though long-term accumulation of advantageous adaptations is necessary for the emergence of complex structures. In biology there is a hot debate on the speed of evolutionary change and the relative weights of macro-structural vs. micro-adaptive changes. In social systems, structural crises play definitely an important role. This pegs the question of the source of crises, and in particularly whether they are endogenously or exogenously constructed, i.e. whether a system evolves to crisis and self-destabilization or whether it is an external habitat-changing event that precipitates change. A meteorite is a clear example of the first; a global economic crisis is a more complicated, as at certain levels it might appear as an exogenous "accident", but to an extent it is the accumulated result of actions at lower levels. Engagement with structural changes, crises and uneven rates of evolution may address a main criticism against evolutionary thinking by social scientists such as Giddens (1984), who claim that evolution over-emphasizes slow adaptation, when social change is often an out-of-equilibrium, crisis and instability-driven process.

6. Science, policy and coevolutionary development

There are very few studies of policy from an evolutionary perspective (Witt, 2003; van den Bergh and Kallis, 2009). Coevolutionary studies are often vague on their policy premises, although they often yield concrete policy conclusions. Some studies rely often implicitly on the normative premise that the maintenance of coevolution itself is a desirable state of affairs and therefore policies should support diversity and experimentation, since they propel coevolution. This is hard to justify without an explicit normative theory. Coevolutionary outcomes are not necessarily beneficial in any particular sense (Witt, 2003; Norgaard, 1994) and diversity or innovation may come at the expense of other social goals (Kallis, 2007b).

A second approach is to assume coevolution as a positive analytical concept that illuminates alternative possible future states, the desirability of which can then be evaluated according to an external value framework (Verspagen, 2009). This fits with Norgaard's definition of coevolutionary development as coevolutionary change that benefits humans. Appraising what counts as benefit rests on an external valuation system (Norgaard, 1994). Nonetheless, many coevolutionary analyses, including those in the present special section, often result in concrete policy conclusions, without however making their valuation system explicit.

Evolutionary studies lack a normative theory (Witt, 2003). If utilitarianism is the normative philosophy of neo-classical economics, what should be the foundation of coevolutionary ecological economics? Without making a choice for the moment, we offer some ideas. One option is the acceptance of an incommensurability of values (Martinez-Alier et al., 1998) and the pragmatism of philosophers like John Dewey and Richard Rorty (Rorty, 1991; Dewey, 1943) for who thought itself is an evolutionary process. For pragmatists truth is not absolute, but tentative through the agreements of all those who investigate and experience the consequences of different truth or value claims. Inquiry has a value in and of itself as a central process in the continuous adjustment of an organism and its environment. This related to the idea of Veblen (1904) about "idle curiosity" being a central feature of human beings. In DB these ideas were synthesized in a strong argument in favor of communal, consensual and deliberative approaches for resolving competing value and truth claims and negotiating what constitutes "coevolutionary development" (see also Dryzek, 1990). From a pragmatist perspective diversity of ideas, experimentation through trial and error, and continuous interaction and learning are desired per se. Maybe somewhat uneasily the pragmatist approach was married in DB with an *a priori* emphasis on precautionary environmental limitations, not so much externally determined, but as a form of human prudence towards an uncertain future. These ideas were synthesized in the vision of a coevolutionary patchwork quilt of discursive communities. These communities are downscaled in terms of material flows, production and consumption and coevolving via direct feedbacks with the local ecosystem, continuously experimenting, learning and negotiating about desirable courses of action (Norgaard, 1994). Coevolutionary development ideas of downscaling, deepening discursive democratization and community investment in collective affairs, and maintenance of diversity and idle curiosity resonate with contemporary discourses about "sustainable degrowth" (Kallis et al., forthcoming).

Coevolution departs epistemologically from positivist notions of the "objective social scientist", whose role is perceived as the contribution to an external policy that in turn intervenes to change social affairs (Norgaard, 1994). Policy and the generation of knowledge are social processes too, endogenous to coevolutionary dynamics. Policies change the world that the social scientist is supposed to describe. This needs not lead to relativism. From a coevolutionary perspective the theorist/analyst is a political actor, participant in the policy process, who generates information and seeks to attract attention (Witt, 2003), i.e. a positioned actor in the struggle of ideas for survival. Scientific theories, including coevolution itself are not absolute claims to truth, but tentative representations and constructions of reality. They are experiments to be judged by communities in terms of their consequences. Such "situated knowledge" (Haraway, 1991) is partial, incomplete and politically motivated, yet critical and politically accountable through inter-subjective conversation (Demeritt, 2002). Making science hence is unavoidably a political act from a coevolutionary perspective; the adjective "political" though should not be mistaken for biased.

The contributions that follow in this special section contribute to various aspects of the coevolutionary theses identified above with theoretical, modelling and empirical works. They make useful interventions in policy debates including water policy, rural development and agricultural policy and harvesting regulation. Authors experiment with new narratives and policy proposals, renewing the diversity of coevolutionary ideas and propelling the evolution of the field. Hopefully other ecological economists will join the project, mutating our ideas to new variants and helping select those ideas that work better.

Acknowledgements

Special thanks to Jeroen van den Bergh for his comments to this paper. We are grateful to the authors, commentators, and reviewers for their strong contributions to this Special Section, and especially to the managing editor, John Gowdy for his patience, support and high quality reviewing process.

References

Alchian, A., 1950. Uncertainty, evolution and economic theory. Journal of Political Economy 58, 211–222.

Aldrich, H., 1999. Organizations Evolving. Sage, London.

Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. Economic Journal 99, 116–131.

Baum, J.A.C., Singh, J.V., 1994. Organization–environment coevolution. In: Baum, J.A.C., Singh, J.V. (Eds.), Evolutionary Dynamics of Organizations. Oxford University Press, New York, pp. 379–402.

Baumgartner, F.R., Jones, B.D., 1993. Agendas and Instability in American Politics. University of Chicago Press, Chicago.

Boschma, R.A., Martin, R., 2007. Constructing an evolutionary economic geography. Journal of Economic Geography 7 (5), 537–548.

Boulding, K., 1978. Ecodynamics: A New Theory of Societal Evolution. Sage, Beverly Hills.

Bowles, S., Gintis, H., 2008. Cooperation. In: Blume, L., Durlauf, S. (Eds.), The New Palgrave Dictionary of Economics. MacMillan.

Boyd, R., Richerson, P.J., 1985. Culture and the Evolutionary Process. University of Chicago Press, Chicago.

Brooks, J., 2010. The Buddha mushroom: conservation behavior and the development of institutions in Bhutan. Ecological Economics 69, 779–795 (this issue).

Campbell, D.T., 1969. Variation and selective retention in socio-cultural evolution. General Systems 14, 69–85.

Clark, E., Tsai, H.M., 2002. Co-evolution under globalization — boundary lessons from Kinmen island. Proceedings of IUCN/WCPA-EA-4 Taipei Conference, March 18–23, 2002, Taipei, Taiwan.

Conrad, J.M., Salas, G., 1993. Economic strategies for coevolution: timber and butterflies in Mexico. Land Economics 69 (4), 404–415.

Costanza, R., Cumberland, J., Daly, H., Goodland, R., Norgaard, R.B., 1997. An Introduction to Ecological Economics. St Lucie Press, Florida.

Cowan, R., Gunby, P., 1996. Sprayed to death: path dependence, lock-in and pest control strategies. Economic Journal 106 (436), 521–542.

Daly, H., 1977. Steady-State Economics. Island Press, Washington D.C.

Deacon, T.W., 1997. The symbolic species: the co-evolution of language and the brain. W. W. Norton.

Demeritt, D., 2002. What is the 'social construction of nature'? Progress in Human Geography 26, 767–790.

Dewey, J., 1943. The development of American pragmatism. In: Runes, D.D. (Ed.), Twentieth Century Philosophy. Philosophical Library, New York, pp. 451–467.

Dove, M.R., 1993. The coevolution of population and environment: the ecology and ideology of feedback relations in Pakistan. Population and Environment 15 (2), 89–111.

Dryzek, J.S., 1990. Discursive Democracy: Politics, Policy, and Political Science. Cambridge University Press, NY.

Dunbar, R.I.M., 1993. Coevolution of neocortical size, group size and language in humans. Behavioral and Brain Sciences 16, 681–735.

Durham, W.H., 1990. Advances in evolutionary culture theory. Annual Review of Anthropology 19, 187–210.

Durham, W.H., 1991. Coevolution: Genes, Culture, and Human Diversity. Stanford University Press, Stanford.

Ehrlich, P.R., Raven, P., 1964. Butterflies and plants: a study in coevolution. Evolution 18, 586–608.

Faber, A., Frenken, K., 2009. Models in evolutionary economics and environmental policy: towards an evolutionary environmental economics. Technological Forecasting and Change 76, 462–470.

Folke, C., Hahn, T., Olsson, P., Norberg, J., 2005. Adaptive governance of social–ecological systems. Annual Review of Environment and Resources 30, 441–473.

Frenken, K., 2000. A complexity approach to innovation networks. The case of the aircraft industry. Research Policy 29, 257–272.

Futuyma, D., Slatkin, M. (Eds.), 1983. Coevolution. Sinauer, Sunderland (MA).

Georgescu-Roegen, N., 1971. The EntropyLaw and Economic Process. Harvard U. Press, Cambridge, MA.

Giddens, A., 1984. The Constitution of Society. Polity, Cambridge.

Gould, S.J., 2002. The Structure of Evolutionary Theory. Belknap/Harvard University Press, Cambridge, MA.

Gowdy, J.M., 1994. Coevolutionary Economics: The Economy, Society and the Environment. Kluwer Academic Publishers, Dordrecht.

Gual, M.A., Norgaard, R.B., 2010. Bridging ecological and social systems coevolution: a review and proposal. Ecological Economics 69, 707–717 (this issue).

Haraway, D.J., 1991. Simians, Cyborgs, and Women: The Reinvention of Nature. Routledge, New York.

Heino, M., 1997. Management of evolving fish stocks. IIASA Working Paper IR-97-062. Laxenburg, Austria.

Hird, M., 2010. Coevolution, symbios and sociology. Ecological Economics 69, 737–742 (this issue).

Hodgson, G.M., 2010. Darwinian coevolution of organizations and the environment. Ecological Economics 69, 700–706 (this issue).

Ingram, H., Fraser, L., 2006. Path dependency and adroit innovation: the case of California water. In: Repetto, R. (Ed.), Punctuated Equilibrium and the Dynamics of U.S. Environmental Policy.

Janssen, M.A., Jager, W., 2008. Stimulating diffusion of green products. Coevolution between firms and producers. Journal of Evolutionary Economics 12, 283–306.

Kallis, G., 2007a. Socio-environmental coevolution: towards an analytical approach. International Journal of Sustainable Development and World Ecology 14, 9–19.

Kallis, G., 2007b. When is it coevolution? Ecological Economics 62, 1–6.

Kallis, G., 2010. Coevolution in water resource development. The vicious cycle of water supply and demand in Athens, Greece. Ecological Economics 69, 796–809 (this issue).

Kallis, G., Martinez-Alier, J., Schneider, F., forthcoming. Sustainable degrowth: where do we go from here? Journal of Cleaner Production.

Kerr, P., 2002. Saved from extinction: evolutionary theorising, politics and the state. British Journal of Politics and International Relations 4 (2), 330–358.

Laland, K.N., Boogert, N.J., 2010. Niche construction, co-evolution and biodiversity. Ecological Economics 69, 731–736 (this issue).

Laland, K.N., Odling-Smee, J., Feldman, M.W., 2001. Cultural niche construction and human evolution. Journal of Evolutionary Biology 14 (1), 22–33.

Laxnminarayan, R., 2001. Economics of antibiotic resistance: a theory of optimal use. Journal of Environmental Economics and Management 42 (2), 183–206.

Lewin, A.Y., Volberda, H.W., 1999. Prolegomena on coevolution: a framework for research on strategy and new organizational forms. Organization Science 10 (5), 519–534.

Lewontin, R.C., 2000. The Triple Helix. Gene, Organism and Environment. Harvard University Press, Cambridge Mass.

Mahoney, J., 2000. Path dependence in historical sociology. Theory and Society 29, 507–548.

Malerba, F., 2006. Innovation and the evolution of industries. Journal of Evolutionary Economics 16, 3–23.

Manner, M., Gowdy, J., 2010. The evolution of social and moral behavior: evolutionary insights for public policy. Ecological Economics 69, 753–761 (this issue).

Margulis, L., 1981. Symbiosis in Cell Evolution: Life and Its Environment on the Early Earth. Freeman, San Francisco.

Martinez-Alier, J., Munda, G., O'Neill, J., 1998. Weak comparability of values as a foundation for ecological economics. Ecological Economics 26, 277–286.

Mayr, E., 2001. What evolution is. Basic Books, New York.

McGlade, J., Murray, R., Baldwin, J., 2006. Industrial resilience and decline: a coevolutionary framework. In: Garnsey, E., McGlade, J. (Eds.), Complexity and Co-evolution: Continuity and Change in Socio-economic Systems. Edward Elgar Publishing.

McKelvey, B., 1982. Organizational Systematics. University of California Press, Berkeley.

Moreno-Peñaranda, R., Kallis, G., 2010. A coevolutionary understanding of agroenvironmental change. A case-study of a rural community in Brazil. Ecological Economics 69, 770–778 (this issue).

J.P.M.Murmann, J.P.M., 2003. Knowledge and Competitive Advantage. The Coevolution of Firms, Technology and National Institutions. Cambridge University Press, Cambridge.

Nelson, R.R., 1995. Recent evolutionary theorising about economic change. Economic Journal XXXIII, 48–90.

Nelson, R.R., 2002. Bringing institutions into evolutionary growth theory. Journal of Evolutionary Economics 12, 17–28.

Nelson, R.R., Winter, S., 1982. An Evolutionary Theory of Economic Change. Belknap Press of Harvard University Press, Cambridge, Mass; London.

Netting, R.M., 1986. Cultural Ecology. Waveland Press, Prospect Heights (IL).

Noailly, J., 2008. Coevolution of economic and ecological systems. An application to agricultural pesticide resistance. Journal of Evolutionary Economics 18, 1–29.

Noailly, J., van den Bergh, J.C.J.M., Withagen, C.A., 2003. Evolution of harvesting strategies: replicator and resource dynamics. Journal of Evolutionary Economics 13 (2), 183–200.

Norgaard, R.B., 1981. Sociosystem and ecosystem coevolution in the Amazon. Journal of Environmental Economics and Management 8, 238–254.
Norgaard, R.B., 1984. Coevolutionary agricultural development. Economic Development and Cultural Change 32 (3), 525–546.
Norgaard, R.B., 1994. Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future. Routledge.
Norgaard, R.B., 2005. Bubbles in a back eddy: a commentary on "the origin, diagnostic attributes and practical application of coevolutionary theory". Ecological Economics 54 (4), 362–365.
Norgaard, R.B., Kallis, G., in press. Coevolutionary contradictions: prospects for a research program on social and environmental change, forthcoming in Geografiska Annaler.
Odling-Smee, F.J., Laland, K.N., Feldman, M.W., 2003. Niche construction. The neglected process in evolution. Monographs in Population Biology, vol. 37. Princeton University Press, Princeton. 472 pp.
Okasha, S., 2003. Recent work on the levels of selection problem. Human Nature Review 3, 349–356.
Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge Univ. Press, New York.
Pennisi, E., 2007. Variable evolution. Science 316, 686–687.
Pierson, P., 2000. Increasing returns, path dependency, and the study of politics. American Political Science Review 94, 251–267.
Porter, T.B., 2006. Coevolution as a research framework for organizations and the natural environment. Organization and Environment 19 (4), 479–504.
Rammel, C., McIntosh, B.S., Jeffrey, P., 2007. (Co)evolutionary approaches to sustainable development. International Journal of Sustainable Development & Global Change 14, 1–3.
Rorty, R., 1991. Objectivity, Relativism and Truth: Philosophical Papers, vol. 1. Cambridge University Press.
Safarzynska, K., van den Bergh, J.C.J.M., 2010. Demand–supply coevolution with multiple increasing returns: policy analysis for unlocking and system transitions. Technological Forecasting and Social Change 77, 297–317.
Safarzynska, K., van den Bergh, J., 2010. Evolving power and environmental policy: explaining institutional change with group selection. Ecological Economics 69, 743–752 (this issue).
Saifi, B., Drake, L., 2008. A coevolutionary model for promoting agricultural sustainability. Ecological Economics 65, 24–34.
Saint Jean, M., 2005. Coevolution of suppliers and users through an evolutionary modelling. The case of environmental innovations. European Journal of Economic and Social Systems 18, 255–284.
Spash, C.L., 1999. The development of environmental thinking in economics. Environmental Values 8, 413–435.
Steward, J.H., 1972. Theory of Cultural Change: The Methodology of Multilinear Evolution. University of Illinois Press, Urbana.
Thiele, L.P., 1999. Environmentalism for a New Millennium: The Challenge of Coevolution. Oxford University Press, New York.
Thompson, J.N., 2005. The Geographic Mosaic of Coevolution. University of Chicago Press.
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830.
van den Bergh, J.C.J.M., 2007. Evolutionary thinking in environmental economics. Journal of Evolutionary Economics 17, 521–549.
van den Bergh, J.C.J.M., Gowdy, J.M., 2000. Evolutionary theories in environmental and resource economics: approaches and applications. Environmental and Resource Economics 17 (1), 37–57.
van den Bergh, J.C.J.M., Kallis, G., 2009. Evolutionary policy. Papers on Economics and Evolution. Max Planck Institute of Economics. #0902.
van den Bergh, J.C.J.M., Stagl, S., 2003. Coevolution of economic behavior and institutions: towards a theory of institutional change. Journal of Evolutionary Economics 13, 289–317.
van den Bergh, J.C.J.M., Faber, A., Idenburg, A.M., Oosterhuis, F.H., 2006. Survival of the greenest: evolutionary economics and policies for energy innovation. Journal of Integrative Environmental Sciences 3 (1), 57–71.
van den Heuvel, S.T.A., van den Bergh, J.C.J.M., 2008. Multilevel assessment of diversity, innovation and selection in the solar photovoltaic industry. Structural Change and Economic Dynamics 20 (1), 50–60.
Veblen, T., 1904. The Theory of Business Enterprise. Augustus M. Kelley.
Verspagen, B., 2009. The use of modeling tools for policy in evolutionary environments. Technological Forecasting and Social Change 76 (4), 453–461.
Vona, F., Patriarca, F., 2009. Income distribution, demand-driven innovations and sustainable growth. Paper Presented in ESEE 2009, 8th International Conference of the European Society for Ecological Economics, 29th June – 2nd July. Ljubljana, Slovenia.
Ward, H., 2003. The co-evolution of regimes of accumulation and patterns of rule: state autonomy and the possibility of functional responses to crisis. New Political Economy 8 (2), 179–202.
Warring, T.W., 2010. New evolutionary foundations: theoretical requirements for a science of sustainability. Ecological Economics 69, 718–730 (this issue).
K.E.Weick, K.E., 1979. The Social Psychology of Organizing. Addison-Wesley, Reading, MA.
Winder, N., 2005. Modernism, evolution and vaporous vision of future unity: clarification in response to Norgaard. Ecological Economics 54 (4), 366–369.
Winder, N., McIntosh, B.S., Jeffrey, P., 2005. The origin, diagnostic attributes and practical application of co-evolutionary theory. Ecological Economics 54 (4), 347–361.
Windrum, C.T., Ciarli, T., Birchenhall, C., 2009. Consumer heterogeneity and the development of environmentally friendly technologies. Technological Forecasting and Social Change 76, 533–551.
Witt, U., 2003. Economic policy making in evolutionary perspective. Journal of Evolutionary Economics 13, 77–94.
Woodgate, G., Redcclift, M., 1998. From a 'sociology of nature' to environmental sociology: beyond social construction. Environmental Values 7, 3–24.
Worden, L., 2010. Notes from the greenhouse world: a study in coevolution, planetary sustainability and community structure. Ecological Economics 69, 762–769.