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Models in evolutionary economics and environmental policy:

Towards an evolutionary environmental economics

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Abstract

In this paper we review evolutionary economic modelling in relation to environmental policy. We discuss three areas in which evolutionary economic models have a particularly high added value for environmental policy-making: the double externality problem, technological transitions and consumer demand. We explore the possibilities to apply evolutionary economic models in environmental policy assessment, including the opportunities for making policy-making endogenous to environmental innovation. We end with a critical discussion of the challenges that remain.

1 Introduction

It is commonly argued that technological innovation will be an important key to decrease the impact of industrial society on the environment. The understanding of environmental innovation – that is, innovation that contributes to the sustainability of the natural environment – from an economic perspective is, however, still limited. Environmental economists working in the neoclassical tradition find it difficult to incorporate technological innovation, since the outcomes of inventive activity cannot be foreseen – not even in a probabilistic sense. Therefore, the treatment of environmental innovation as a maximization problem is of limited practical relevance [1]. Ecological economists may be better able to analyse environmental innovation because they work outside the maximization framework. Yet, hitherto they have been relatively silent on environmental innovation.

With neoclassical and ecological economics having failed to develop a systematic research programme on environmental innovation, evolutionary economics emerged as an alternative and promising framework [2]. In the last fifteen years or so, we witness an increasing number of contributions in environmental economics adopting an evolutionary perspective, including conceptual frameworks [3-7], empirical studies [8-12] and policy-oriented discussions [13-16]. More recently, scholars have started to develop formal evolutionary models in environmental studies, both explanatory and prospective [17-30]. These efforts reflect a further deepening of the evolutionary programme in the area of environmental studies, which opens up possibilities for application in policy-making. The goal of this paper is to provide a systematic review of the recent efforts in evolutionary modelling in environmental studies, and to assess their implications for environmental policy-making.

We apply the following structure. We first briefly discuss evolutionary theory and its application to the study of the economy (section 2). We go on to discuss three areas in which an evolutionary approach in environmental economics has a particularly high value-added for environmental policy-making: the double externality problem, technological transitions and consumer demand (section 3). We then take up a 'reflexive' approach to the role of government in environmental innovation from an innovation systems approach, exploring opportunities for making policy-making endogenous to environmental innovation (section 4). We end with a discussion of the methodological challenges that remain (section 5).

2 Defining properties of evolutionary dynamics

Evolution is an extremely strong concept for understanding the dynamics in the world surrounding us. After the publication of the seminal works by Charles Darwin, evolutionary theory was mainly elaborated and applied in the sphere of biology, which still leads many present-day observers to consider evolutionary theory as a biological theory. Following this view, applications of evolutionary theory outside biology are often considered 'metaphorical'. However, various authors have pointed out that evolution is a general principle based on variation, selection and replication [31-33]. With the advent of computer simulation, the general evolutionary principle has been formalized in a number of canonical models, for example genetic algorithms [34], evolutionary games [35], random fitness landscapes [36] and multi-agent models [37, 38], which are applied both in biology and other disciplines like economics, sociology, psychology, language studies, science studies, technology studies and management.

In biological evolution, mutation and crossover of chromosomes are the principle generators, and natural selection is the test. Natural selection operates by differential offspring as the fitter variants have their chromosomes replicated in more offspring than less fit variants. In technology evolution, the unit of analysis analogue to genes is harder to identify. Most often, scholars identify organisational routines as the unit of analysis [39]. Routines enable organizations, in particular firms, to produce particular technological artefacts at a certain level of economic efficiency. Routines are replicated vertically (through the creation of new firms as spin-offs or subsidiaries of existing firms) as well as horizontally (through imitation among existing firms). Investments in Research & Development (R&D) generate new routines leading to new artefacts. Innovative activity can thus be considered as a search process in which firms try, through trial-and-error, to improve the quality of their outputs or reduce the costs of output of a given quality. The fitness of artefacts is thus best thought of as value-for-money [40]. The selection process operates by differential profits among firms, as fitter artefacts are sold at higher profit margins than less fit artefacts. Consequently, firms producing the fitter artefacts have higher changes of survival than firms producing less fit artefacts. Note, however, that selection in modern societies does not only depend on sales but also on the extent technologies are socially legitimate as reflected in governmental regulations and social norms.

A second property of evolutionary theory lies in the population framework, which basically defines the level on which evolution works. Fisher [41] identified that the frequencies of various genes within a population changes over time according to their fitness. Units or individuals with above average fitness increase in frequency in a population, while units with below average fitness decrease in frequency and eventually become extinct. The population perspective can also be distinguished in markets where firms compete through innovation. Firms employing different technologies will be characterized by different fitness as expressed in profits. An evolutionary perspective thus rejects the assumption that firms all use, under the same conditions, the same technology. Yet, in the absence of further innovation and under specific conditions, market selection will lead firms that use the best performing technology to be the only survivors, akin to the process of natural selection [39, 42].

It is sometimes argued that technological innovation is not an evolutionary process because technological innovations do not occur at random, while biological mutations do so. Unlike biological evolution, the direction of innovative search is not determined at random, but is rooted in technological paradigms that guide the search behaviour of firms [43]. This also means that technological development is, to some extent, a self-fulfilling prophecy: technological paradigms create widespread expectations about the future potential of a particular technology thereby mobilising resources and supporting institutions, which in turn accelerate the development of a technology thus confirming the expectations underlying the resources and institutions [44, 45]. Still, the process of technological development can be considered as an evolutionary process, because agents will always remain fundamentally uncertain about the outcomes of their investments in R&D. As a result, the success of their search activities will only become apparent ex post depending on the sales figures and profit margins.

A specific phenomenon in evolutionary processes, with special relevance to technological development, is frequency-dependent selection. Frequency dependency means that the fitness of a particular genotype or technology depends on its frequency in the population. Positive frequency dependence means that the fitness of a genotype or technology increases with the number of copies in the population. Though not very common in biological evolution, most technologies are positively frequency dependent, because of increasing returns to adoption: the more a technology is used, the higher its utility for users becomes [46, 47]. Well-known examples are telephone, fax and email, or more generally, communication technologies, for which utility increases as with the number of adopters. Though most apparent in communication technologies, increasing returns to adoption are relevant to virtually all technologies for various reasons: more users render production costs and prices to be lower, standardization increases compatibility with other technologies, more users generate more information about the technology reducing the risk in adoption, more users generate related markets for auxiliary products and services, and more users generate more political power to change institutions as to support the further development and use of a technology.

Formally, increasing returns to adoption imply that Fisher's differential equation [41], in which the frequency of particular genotype/technology changes solely according to the difference between its fitness and the fitness of competing entities, needs to be extended for application in the analysis of innovations. The original Fisher's equation is characterised by a *unique equilibrium* as the fittest technology will eventually come to fully dominate the population. When increasing returns are present, fitness is not only dependent on the 'intrinsic' fitness of the technology, but also on its frequency in the population. As a result, a new technology with higher intrinsic fitness but few adopters, will have difficulty to invade the population, even though adopting the new technology by all adopters, would lead to a fitness gain for all. In this case, the economy is said to be 'locked in' in a sub-optimal Nash equilibrium. A differential equation selection model of this kind is characterised by *multiple equilibria* with the dominance of either the existing or the new technology being stable Nash equilibria [48]. Consequently, some form of coordination or collective action among actors is required to 'unlock' an existing technology to give room for an alternative technology to diffuse.

3 An evolutionary economic approach to environmental policy

Evolutionary environmental economics complements neoclassical and ecological approaches in its emphasis on environmental innovation. From the recent progress that is being made in applications of evolutionary economics to environmental issues, we distinguish three main areas where an evolutionary economic approach shows particular added value in environmental research: (1) the 'double externality problem', (2) technological transitions, and (3) consumer demand.

3.1 The double externality problem

Generally, investments in R&D are inhibited when results from that investment spill over to competing firms. Moreover, investments in environmental innovations are also inhibited by the fact that the private return on R&D in environmental technology is less than its social return if prices do not adequately reflect negative externalities such as environmental impact [49]. Thus, there are two reasons why firms will be reluctant to invest in environmental R&D as they cannot fully appropriate the social returns as private returns, a condition referred to as 'the double externality problem'.

An evolutionary economic approach provides a systematic framework to develop the concept of double externality into a fully-fledged theory. In particular, the notion of technological regime is relevant here, referring to "combinations of opportunity and appropriability conditions and degrees of cumulativeness of technological advances" [50, p. 453]. The concept of technological regime was first introduced in a simulation model of innovation and industrial dynamics by Winter [51], who distinguishes between an entrepreneurial regime and a routinised regime. The entrepreneurial regime is generally associated with emerging industries, while the routinised regime is associated with mature industries. In emerging industries the development of innovations relies on grasping opportunities external to the firm, while in mature industries innovative activities depend rather on the knowledge residing within the firm, reflecting a higher degree of incrementalism in comparison to the entrepreneurial regime. The cumulative nature of innovation is reflected in the higher probability of innovation and the higher degree of incrementalism in the routinised regimes compared to the entrepreneurial regime. The results of the Winter model show that innovation in the entrepreneurial regime is driven by the entry of new firms, while in the routinised regime a subset of leading firms are responsible for most of the innovations. The model results also show that the lead firms were significantly older than the average firm indicating persistent first-mover advantages. A follow-up model by Klepper [52] replicates both regimes in a single model where the transition from the entrepreneurial regime towards the routinised regime is generated endogenously in the model. Here, firms entering in the early stage of industry evolution grow bigger and become more experienced in doing R&D. This leads to an industry shakeout during which few successful firms survive while most are forced to exit. As a result, a stable oligopolistic market structure emerges. The hypothesised technological regimes and their impact on innovation dynamics and market structure have been validated empirically for a long series of industries [50, 53-58].

Depending on the parameters for opportunity, appropriability and cumulativeness, some industries will suffer more from the double externality problem than other [59]. If opportunities are abound and appropriability conditions are favourable, firms will have strong incentives to invest in environmental innovations. In such environments, price measures may well trigger firms to devote more efforts to environmental technologies. If, by contrast, opportunities are few and inventions are difficult to appropriate, such measures may have much less effect. In such contexts, price measures are expected to have a much greater impact if complemented with investment in public R&D and programmes that transfer publicly funded research to industry.

A high degree of cumulativeness of innovations will induce incumbent firms to develop incremental innovations along a particular technological trajectory [60]. This can be favourable for environmental innovation if such innovations can be integrated in the current trajectory. However, if a radical environmental innovation is required, a high degree of cumulativeness may block innovation [61, 62]. Policy based on price measures will in this case mostly lead to higher costs for firms and consumers rather than provide innovative incentives, Future modelling exercises on industrial dynamics and technological regimes can study the static and dynamic welfare implications of alternative environmental policy instruments in the context of specific technological regimes and industries.

Environmental policy based on the standard economic assumptions will often overlook cost-effective opportunities to reduce the cost of achieving environmental quality [63]. In the evolutionary approach, on the other hand, a firm may profit economically by investing in environmental innovations leading to a (temporary) monopoly [64]. Such monopolies may also be created by the introduction of minimum environmental standards, which are often considered effective in raising general environmental performance of technologies. The welfare effects of such instruments are, however, likely to be more complex [23]. Overall environmental performance will generally increase as production below the minimum standard is prohibited, but entry barriers to the market are raised creating negative welfare effects due to lower levels of competition. Furthermore, standards may cut off alternative technological trajectories that do not meet the standard, but may have been promising in improving other environmental dimensions. Future modelling exercises can assess the joint effects of environmental policies as to provide a comprehensive assessment of welfare effects.

Evolutionary models can also be useful to study the interplay between industrial and environmental policy [65]. Environmental regulations that are intended to stimulate environmental innovation involve extra costs for domestic companies, yet also may generate export opportunities as a lead market. A model combining environmental innovation, industrial dynamics and international trade could provide interesting insights here. One expects the technological regime to affect how lead markets will emerge, particularly with respect to the (country or sector specific) conditions of appropriability of technological development, as well as the ability of firms in other countries to imitate and further develop the technology. Such models can also shed light on current debates about the need and obstacles for technology transfer of environmental innovations between developed countries to less developed countries, for the latter countries to be able to fulfil their environmental objectives in an efficient manner.

In conclusion, evolutionary economics provides a range of conceptual models addressing the interplay between industrial dynamics and technological innovation. Such models are particularly useful to help understand the specific nature of the double externality problem in particular industries, and the static and dynamic welfare effects different environmental policies will likely produce. As effects differ across different technological regimes, this approach will highlight the importance of the industry-specific context in policy design.

3.2 Technological transitions and niche management

A technological transition is generally understood as the substitution of a large complex technological system by a new system. For example, the transition from horse and carriage to the internal combustion engine car system, and from the internal combustion engine car system to a (future) fuel-cell car system. Such a transition involves a ‘technological paradigm shift’ during which society abandons certain patterns of solutions to certain problems and develops a new pattern of solutions [13, 66, 67]. Technological transitions have become a focal issue in environmental policy of some western European countries, aiming for large-scale changes to improve the sustainability of major technological systems. Important issues in transition policy relate to unlocking the present technological system, to focus track to an alternative system that is environmentally more attractive, and to allow for making strategic use of windows of opportunities in time.

Technological transitions are characterized by the systemic nature of the changes involved, as well as by the large number of heterogeneous agents and institutions, the general large scale of change and long time horizons. The systemic perspective relates to the existence of strong increasing returns to adoption and scale. Bruckner et al. [48] have developed an elementary evolutionary model to understand the conditions that lead to technological substitution in the presence of strong increasing returns. They show the difficulty for a new technology to take over the market, even if this new technology is technically far superior to the incumbent technology. Only when a critical mass of adopters simultaneously switches to the new technology through some form of coordination, all others will follow and adopt the new technology as well. This model only applies in markets with homogeneous products; in markets with heterogeneous products, there are various user groups that differ in their valuations of a technology's characteristics. In such environments, new technologies can be introduced in niche markets when a user group is willing to pay a significant premium for the superior characteristic. Once introduced, users and producers start learning and will introduce subsequent improvements. Such a gradual process allows the technology to diffuse niche-by-niche [66, 68].

The fragmentation of markets can thus be understood in terms of heterogeneity of demand preferences, a notion that offers good opportunities for exploration with evolutionary models [69]. The impact of heterogeneity of preferences on technological change has been studied extensively in evolutionary models of technology adoption using a variety of modelling approaches, including diffusion models with increasing returns [69-71], co-evolutionary models of users and producers [17, 24, 29, 72] and extensions of the Nelson-and-Winter model [58, 73]. These models generally confirm the conclusion that niches, provided by consumer groups with deviant preferences, are indeed important for technological transitions to take place, as the new technology can be developed within the niche before being introduced in the mass market. Such models conceptually support policy measures and regulations aimed to have environmental technologies mature in niche markets, a notion that has been recognized in the policy concept of strategic niche management (SNM) [13, 14, 74]. The next step is to apply these models empirically by calibrating parameters and initial conditions from technical data sources [for an example, see 25].

Policies following the above argument can be summarized as aiming at ‘unlocking’ a socio-technical system to provide opportunities for alternative, more sustainable systems to develop and diffuse. A second line of thought in policy oriented at technological transitions deals with avoiding a new lock-in into a sub-optimal technological system [47, 75-77]. A strategy aiming to un-lock the incumbent technological system may actually favour the development of specific alternative (sub-optimal) system, even if it is not the policy objective to do so. In order to avoid an early lock-in into a new technology, the preservation of technological diversity can be a useful policy objective, even though few systematic methodologies have been developed to assess empirically or conceptually the value of diversity [78, 79]. Preservation of a portfolio of various technologies helps to foster a wide range of technological developments for a while, gaining information about the exact properties and costs of all alternatives. Clearly, such a policy is juxtaposed to the regular policy theme of efficiency [16].

Another policy option in the face of uncertain technological development lies in preserving the flexibility to reach a best fitness option in the future. Building on the concept of fitness landscapes from Kauffman [36, 80], and transferred to management science by Levinthal [81], Schwoon et al. [19] have developed a methodology to describe all technology options as a specific combination of subsystems, and a transition path as a series of changes in subsystems leading to a transition from a current system to a new system. Such a path can be thought of a sequence of mutations in subsystems, each of which incrementally improves the overall system’s fitness in terms of, for example, fuel efficiency or environmental performance. Such paths end when a local peak in the ‘fitness landscape’ is encountered, which can no longer be improved by an innovation in a subsystem. Using empirical data on the relative performance of all conceivable car systems, Schwoon et al. [19] analyse the possible transition paths through the landscape and as the flexibility of such paths in that re-routing exist if unforeseen problems arise. This methodology shows how progress can be made in various directions without cutting off alternative development trajectories that may turn out to be promising at a later stage but which are presently unforeseen.

The policy problems of un-locking existing technological systems and avoiding early lock-in highlight the strategic value of timing. The effect of specific policy interventions is highly dependent upon the timing of its implementation. A policy intervention supporting a new technology will have little effect if the incumbent technology is still in full development and few niche markets exist, while policy intervention may have a decisive effect on the development of a specific technology when development in the existing system slows down and niche markets are many. More generally, while socio-technical systems are often stable for some time, they provide ‘windows of opportunity’ for policy intervention at times when the stability of the socio-economic regime temporarily decreases

[47, 82]. The concept of windows of opportunity basically refers to 'the right time' for political action aimed at stimulating environmental technologies [83]. Various policy strategies related to windows of opportunity can be conceived of, such window preparation, window creation and window utilisation [84]. It should be noted that windows of opportunity do not inherently arise from an evolutionary modelling exercise; what follows from the model are critical values or thresholds and windows of opportunity are the policy relevant interpretation of these points. The added value of evolutionary modelling lies in the identification of critical values under different parameter settings, which could serve as systemic tipping points.

3.3 Dynamics of consumer demand

Economists traditionally understand consumer demand as stemming from private preferences, which are simply 'revealed' through their actual choice behaviour. This perspective allows to analyse the economic system without having to analyse preference formation and preference change. Consequently, policies aiming at changing consumption patterns have relied heavily on price instruments such as taxes and subsidies, rather than on policies that may affect people's preferences.

Notwithstanding the effect of price measures on consumption patterns, it is important to advance understanding of the individual and social dynamics that bring about preference changes. Some significant contributions have been developed by evolutionary economists and psychologists to address this issue [17, 69, 85-88]. A key concept in the evolutionary approach of consumption and demand lies in the dynamics of changing preferences, particularly through the interaction of demanding agents with each other or with other players on the market. We distinguish between three topics that we discuss below: bounded rationality, moral behaviour and conformism, and interaction between user and producer.

Consumer theory in evolutionary economics is based on the concept of bounded rationality: consumers cannot know about the properties of all goods on the market because of constraints in information, knowledge or effort. Therefore, consumers develop routines, based on previous consumption experiences: consumers learn to consume [88]. Since consumers differ in terms of their knowledge and skills, diffusion will generally start with 'sophisticated users'. The success of these early innovations is not necessarily replicated in mass markets with less sophisticated users. Environmental policy that aims to accelerate diffusion by using on price instruments alone may be not successful if not accompanied by training or information provision, for example through the use of eco-labelling [26].

Bounded rationality also leads consumers to rely on information they receive from fellow consumers. Agent-based modelling provides a good framework for the evaluation of interaction among consumers, who are individually attributed with heterogeneous characteristics, preferences and abilities [17, 29, 30]. A specification of this approach implies that the social network structure can bear effects on the probability and speed of diffusion of innovations, which can be modelled as the percolation of information among agents located on a grid structure [89, 90]. Percolation in adoption means that an agent becomes aware of a novel product only when a “neighbour” buys it for the first time. Whether the agent subsequently adopts the product or not depends on the agent’s preferences as indicated by its minimal quality requirement. These assumptions are sufficient to reveal the tipping point between failed diffusion and mass diffusion: once a product passes a threshold of quality it will suddenly diffuse widely. Extending the model with increasing returns and imitation among consumers shows the three-stage dynamics of technological paradigms: during the pre-paradigmatic phase several paradigms co-exist in different niches, then one paradigm emerges to dominate the market due to network externalities, and during the mature phase the paradigm is elaborated in various sub-variants [70].

Consumers do not only differ in knowledge and skills, but also in preferences. Environmentally concerned consumers may be more willing to pay a premium for a particular good with less environmental impact. Such intrinsically motivated consumers are often driving the first stages of an innovation as they provide a niche market for environmental products. In the following stages other consumers may imitate this preference, possibly because of conformism rather than by intrinsic motivation of environmental concern. Frey [91] distinguishes between intrinsically motivated consumption behaviour and externally motivated behaviour. Environmental policies such as regulation or taxes can psychologically affect the intrinsic motivations of consumers as the locus of control has shifted away from the consumer. Once behaviour is being demanded by policy instead of chosen voluntarily, intrinsic motivations for certain behaviour tend to decrease. Weak enforcement of regulations or tax exemptions for particular groups may further undermine intrinsic motivations. At the same time, environmental policies may also strengthen intrinsic motivation as consumers are informed about what type of consumer behaviour is morally expected from them, especially in conformist societies. Such a behavioural perspective clearly has important implications for the assessment of the expected effectiveness of environmental policy. More generally, the understanding of why some environmental technologies (or policies promoting them) fail or succeed, requires an understanding of the social dynamics underlying preference change, including such mechanisms as peer pressure, imitation, status, conformity, etcetera [25]. The distribution of heterogeneous consumer preferences can be of key importance in determining whether environmentally friendly technological paradigms evolve and substitute more harmful paradigms[29]

Of specific interest is the involvement of users in the innovation process itself. Though research on this topic goes back at least twenty years [92], the emergence of ‘open innovation’ models where users actively participate in the innovation process is more recent [93, 94]. Note here that users need not only be consumers, but can also refer to employees. Explicit evolutionary models of open innovation are still to be developed, although some progress is being made in related topics such as open source models [95] and social network models [96]. The concept of open innovation can be particularly important for understanding the development of environmental innovations, where some users very actively co-develop new technologies. In particular, ‘niche users’ are often crucial as the frontrunners to a technology’s emergence and success [13, 92]. Future decentralized infrastructure systems (e.g., in electricity production) may further spur such user involvement as innovations can be readily implemented and exploited by users individually or collectively.

4 A co-evolutionary perspective on institutions and policy

The applications of evolutionary models for environmental policy-making are primarily in the area of ex ante assessment of static and dynamic welfare effects of environmental innovation policies. In this, evolutionary models can be used in the same way as any economic model in this area: to explore likely outcomes of different policy interventions and to evaluate the costs and benefits. However, evolutionary economics can also be used to understand the complex dynamic between institutions, government policy and technological development in a ‘reflexive’ manner. That is, government behaviour need not be considered only as an independent variable, but also a dependent variable. This type of research can also help to understand why certain countries have been more effective in environmental policies.

Conceptually, the presence of co-evolutionary dynamics requires a more integrated perspective on the full system of innovation, rather than on the development of a sole technology. The concept of National Innovation Systems has been developed to capture the interdependent nature of producers, users, institutions and governments and to understand the differential innovative success of countries[97-100]. In an innovation system, agents and institutions all perform specific functions such as financing, entrepreneurial activities or research, which inter-relate to acquire innovative momentum [4]. An innovation system perspective allows for the conceptual incorporation of feedback mechanisms among agents’ activities and cumulative processes of collective learning [5]. In the context of environmental (innovation) policy, national systems also differ significantly with respect to the institutional arrangements and relationships among primary agent groups, as has been shown in a series of studies on the development of wind turbines [101-103]. Institutional specificities also imply that successful policies cannot be easily transferred from one country or region to another [104, 105]. The innovation systems approach is not necessarily applied at the national level, but also at the sectoral scale [59] or at the level of a technological innovation systems [4, 11, 106], in order to account for sectoral or technological differences in the interaction logic between users, producers and governments. In technological innovation systems specifically, institutions develop ‘along the way’ in a co-evolutionary relationship in which policies are adjusted to emerging technological paradigms and paradigms are adjusted to policies [107, 108]. Environmental innovation policy thus requires to take into account the institutional context of a technological development in which technological change, consumer demand and institutional settings co-evolve and mutually interact [29, 30]. A particularly interesting model in this line has been developed by Windrum et al. [23, 30, 59, 109], where endogenous paradigm shifts are modelled in the light of heterogenous consumerd and their tradeoffs in price, quality and environmental impact. Firms respond to the incentive structures provided by the distribution of consumer preferences within a market and have a strong incentive to improve the environmental performance of their products if a high value is placed on environmental utility and if the level of global pollution rises to such as extent that the average level of utility of all consumer classes becomes negative.

Few evolutionary modelling approaches have been developed so far to describe interactions and relational structures in a system, in order to study development of a system’s structure, the evolution of relations and interactions within a system, and to understand properties of emergence in relating micro-scale activities to system properties [20, 110, 111]. Other directions of modelling explore the co-evolution of economic and ecological systems, for example when studying the common pool problem of fisheries [27] or the effects of pesticide use [18]. The behavioural rules that are being explored and selected, can be thought of institutions co-evolving with the ecological system.

Another possible approach uses the concept of coupled fitness landscapes [36, 112, 113]. Such models are especially useful to study the co-evolution of two or more technologies, where changes in one technological can affect, positively or negatively, the fitness of other technologies. This model can explain why sudden avalanches of innovation can take place as one innovation triggers other innovations in co-evolving technologies. Similarly, one can model the co-evolution of technological and institutional change using coupled fitness landscapes where one landscape represents the fitness of a technology (given consumer preferences) and the other landscape represents the fitness of alternative policies (given voter’s preferences).

5 Conclusions and challenges

Uncertainty is an inherent element to social dynamics, because of the bounded rationality of agents, the unpredictability of innovation and the existence of multiple equilibria. Evolutionary economic models recognise this uncertainty and make it explicit, thus taking it out of the usual black box and showing the wide spectrum of possible futures. Socio-economic evolutionary models are particularly useful to simulate market dynamics for experimentation with ‘what if’-questions. An evolutionary simulation model, indeed most economic models, can therefore be seen as a laboratory for social experiments, which can be very helpful to study variations in the mechanisms and assumptions in the model (sensitivity analysis) and to explore exogenous variations in, for example, policy measures or changes in behaviour (scenario analysis) [114].

It is probably fair to say that the strength of the evolutionary approach lies in its strong microeconomic foundations. It builds on behavioural theory of the firm and provides a more realistic description of the technological black box. An important weakness lies in the lack of empirical testing of existing evolutionary models, due to the fact that evolutionary models generally have (too) many parameters [115]. A key challenge to tackle this issue is to improve the hypothesising of the linkages between the micro and the macro level. These linkages follow some fundamental rules of system complexity, the main characteristic being its non-linear properties. Such aggregation requires to formalise the characteristics of agent behaviour, firmly rooted in social theory and empirical reality. However, evolutionary models in general and agent-based models in particular have a problematic relationship with empirical data, since this involves an assessment of the extent to which the model is a good representation of the process that generated a set of observed data. A major challenge therefore, is to come to simplified canonical evolutionary models that encompass the fundamental non-linear relations only. Complexity theory and its applications to technological innovation and diffusion processes, provide good candidates models in this direction [116].

A second way to deal with the problem of a multitude of parameters is to bound these values to certain ranges on empirical ground. For many environmental technologies, technical information is available that can be used for this purpose. And, in certain instances, information about user groups can be used to specify the selection environment in a detailed manner. By doing so, the size of the parameter space can be reduced drastically allowing the researchers to better understand the possible behaviours of the model and the likelihood of various outcomes. Similarly, one can sometimes derive probable initial conditions from empirical data, which would further reduce the possible behaviours a model can display.

Apart from the empirical validation of parameter values and initial conditions, the behavioural assumptions and feedback mechanism require empirical validation. Typically, such empirical evidence is derived from previous studies. However, interaction with the relevant stakeholders also provides a way to validate the model empirically. It is therefore useful for evolutionary model builders to work in close association with experts in a particular field [114].

Evolutionary economics provides a range of innovation models, allowing the policy-maker to assess ex ante the static and dynamic effects of different policy instruments. In particular, industrial dynamics models distinguishing between technological regimes allow policy-makers to assess policy instruments in different industry contexts. Furthermore, a number of methodologies have been developed to understand the conditions under which technological transitions may occur and the specific role of niche users herein. A future challenge for evolutionary economists is to develop models in which the role of government can be made endogenous within an innovation system perspective. Concluding, the use of socio-economic evolutionary simulation tools in environmental policy assessment and evaluation offers very promising opportunities for policy makers, social scientists, environmental experts and formal modellers, whose cooperation could give rise to an exciting new branch of truly interdisciplinary science.

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