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Towards a new complexity economics for sustainability

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Some of the most important and urgent topics requiring economic analysis and policy advice are the problems of climate change and environmental sustainability, and what can be done to alter corporate and individual behaviour to deal with these issues. Neoclassical economists tend to focus on market solutions such as carbon trading, drawing on ideas of perfect rationality of actors and the appropriateness of 'marginal' analysis. To link such policies to the whole range of potential actions, from legislative and regulatory to changing individual behaviours, requires the economy and society to be analysed in its full complexity, recognising that 'marginal' analysis can be not just irrelevant but positively harmful when the need is for systemic shifts in economic and social trajectories. This article draws upon a seminar series on complexity economics to consider how heterodox economic analysis can be brought to bear on the issue of the environment, to develop a realistic policy agenda for change.

Key words: Complexity economics, Climate change, Sustainability
JEL classifications: Q01, Q5, Q57

1. Introduction

The impacts of human systems of production and consumption on natural systems that are crucial for maintaining and enhancing human well-being have been well documented, in relation to global climate change (Intergovernmental Panel on Climate Change, 2007), food insecurity (Food and Agriculture Organization, 2010) and wider ecosystem services (Millennium Ecosystem Assessment, 2005). Proponents of the

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concept of 'sustainable development', which may be defined as 'meeting the needs of the present without comprising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987), have argued that meeting environmental, social and economic objectives is strongly interdependent. This has been recognised by world leaders in the Millennium Development Goals for tackling extreme poverty by 2015 (United Nations, 2000) and efforts to reach a global agreement on mitigating climate change (United Nations Framework Convention on Climate Change, 2010).

It is becoming increasingly recognised that neoclassical economics is inadequate to address these challenges, because the underlying assumptions of individual rationality and marginal changes are inappropriate. Sraffa (1926) pointed to the weakness of the marginal approach for an understanding of real-world economic processes and Marcuzzo and Rosselli (2011) report on Sraffa's arguments against marginalism more generally. In a nice passage, they quote Marshall's explanation of the relevance of marginalism, followed by Sraffa's doubts:

> … an alert manager is constantly weighing the net product in saving of time and of annoyance to passengers, that will accrue from the aid of a second guard on an important train and considering whether it will be worth its costs. (Marshall, 1920, p. 5)

> Sraffa never found this representation convincing, and made reference to it on various occasions over the years. He eventually wrote on 29 March 1963:

> This suggests that his [the alert manager's] *main* task is to sack a porter here, add a coach to a train there, or shorten a platform elsewhere. The idea is that the process of change can be reduced to a continuous process, like shortening platforms. 'A penny is the basis of a million', and so a process of shortening, adding, sacking in detail is the route from one position to another. In Marshall's view the 'alert Dr. B' never needs to take a bird's eye view of his enterprise. (D3/12/42/12)

> (Marcuzzo and Rosselli, 2011, 224–225)

Marcuzzo and Rosselli (2011) go on to describe Sraffa's more fundamental objections to marginalism, not just for its lack of realism but also the logical impossibility of attributing effects to marginal additions of factors, when what one is really comparing is two states of the world and the difference between them is not due simply to the additional factors, but to the fact that all factors may be relating and operating differently in the second regime. But the above description of the railway manager is a nice illustration of the need to go beyond marginalism to take 'a bird's eye view', especially since this broader vision is absolutely vital to seeing the bigger picture as regards environmental sustainability and to envisioning the sort of policy measures that will be needed to achieve it.

Mainstream environmental economics attempted to reconcile the ideas of neoclassical economics with social and environmental impacts through the concept of 'externalities'—i.e. social and environmental costs that are not paid for by those responsible for the economic activities that create those costs (Pigou, 1932; Pearce *et al.*, 1989). Hence, the usual starting point for environmental policies is to aim to 'internalise these externalities', e.g. by setting up measures that put a price on carbon emissions, such as the European Emissions Trading Scheme. However, the Stern Review on the Economics of Climate Change argued that climate change has a number of distinguishing features that economic analysis must address: it is global in its causes and consequences; the impacts are long-term and persistent; uncertainties and risks are pervasive; and there is a serious risk of irreversible changes with non-marginal economic effects (Stern, 2007, p. 25). These features also apply to other environmental challenges, such as biodiversity loss, and imply that economic analysis based on simply internalising externalities and finding optimal responses by equating marginal costs and marginal benefits is inadequate to address these challenges. Responses will also require other actions, including promoting technological and social innovation towards particular ends, such as developing and deploying low-carbon technologies, and encouraging change away from high-impact behaviours and practices. However, economic analysis of this introduces further externalities and uncertainties, such as spillover effects, whereby firms underinvest if they perceive that others may be able to benefit from their discoveries, and learning effects in technology deployment (Arrow, 1962), which interact with the environmental externalities and uncertainties (Rennings, 2000; Grubb and Ulph, 2002; Jaffe *et al*., 2005).

Hence, many ecological economists have argued that economic analysis needs to be fundamentally reframed in a way more consistent with the systemic interdependence of economic activity on natural resources and waste-assimilation processes (Boulding, 1966; Daly, 1977; Costanza, 1989; Common and Stagl, 2005). In parallel with this work, other streams of heterodox economic thinking have been developing approaches to understanding processes of social, technological and industrial change that go beyond neoclassical economics. Further conceptual resources come from interdisciplinary research on complex systems, which investigates how complex properties and behaviours arise out of the interactions between simpler elements in a system (Mitchell, 2009). A burgeoning research programme on 'complexity economics' seeks to apply these ideas to the analysis of economic systems (Foster, 2005).

This paper aims to review and synthesise selected insights from 'complexity economics' and its application to addressing pressing environmental and sustainability policy challenges. This draws on ideas presented and discussed at five research seminars held in the UK and Italy between 2008 and 2010. Participants at these seminars included representatives from a number of UK government economic, business and environmental departments, consultancy firms and non-governmental organisations, as well as leading UK and European academics. Informal and formal feedback from participants indicated that these ideas could usefully inform the development of economic thinking and policy analysis in these areas and would benefit from being shared with a wider audience. This paper thus aims to contribute to a debate on the relevance—and need for further development—of these ideas, without claiming to provide a full survey of the expanding literature.

Section 2 of the paper introduces the main intellectual strands of thinking that this research programme draws on, including complex systems thinking, evolutionary and institutional economics, ecological economics, social and psychological understanding of human behaviour, and socio-technical transitions theory. Section 3 introduces a set of key tools, techniques and ideas that are being developed to apply the insights generated by these theoretical approaches, including systems analysis, input–output analysis, social network analysis, coevolutionary approaches and new economic thinking. Section 4 focuses on the crucial question of the compatibility of the continuing pursuit of economic growth in industrialised countries with social and environmental sustainability. Section 5 draws conclusions and initial policy implications.

2. Complexity economics

One of the challenges of applying complexity thinking to economic problems, such as sustainability, is that there is no one widely accepted definition or understanding of complexity, raising significant ontological issues (Perona, 2007; Rosser, 2010). Hence, we argue that 'complexity economics' is best thought of as a research programme that seeks to draw on a range of thinking and approaches, rather than as a single coherent body of thought. In this paper, we draw out those insights from this research programme that we consider to be particularly relevant for addressing environmental and sustainability challenges.

The term 'complexity economics' was coined by Brian Arthur of the Santa Fe Institute (Arthur, 1999), leading to the idea of economies as 'complex adaptive systems'. Summarising the literature, Beinhocker (2006) argues that this approach differs from the standard view in at least five ways:

(i) *Dynamics*: economies are open, dynamic systems, far from equilibrium.
(ii) *Agents*: they are made up of heterogeneous agents, lacking perfect foresight, but able to learn and adapt over time.
(iii) *Networks*: agents interact through various networks.
(iv) *Emergence*: macro patterns emerge from micro behaviours and interactions.
(v) *Evolution*: evolutionary processes create novelty and growing order and complexity over time.

Drawing on ideas of Georgescu-Roegen (1971), Richard Nelson (2005) and others, Beinhocker (2006) argues that an ongoing process of coevolution of physical technologies, social technologies (i.e. institutions or ways of coordinating human activities) and business plans underlies the creation of wealth in industrialised countries, notably as property rights-based market economies encourage technological and social innovations for meeting (and creating) consumer demands. He argued that this approach can inform how to enhance and spread more widely this prosperity, whilst recognising the limits imposed by human impacts on the planet's climate and ecosystems. However, in order to remain with the limits imposed by the planet's climate systems, an improvement in carbon productivity (GDP/CO_2e) of 5.6% per year, or 10 times by 2050, is needed. This is three times the rate of labour productivity improvement achieved through the Industrial Revolution (Beinhocker, 2008).

Complexity economics draws together insights from a range of approaches that challenge conventional economic thinking, including evolutionary economics and institutional economics. Each of these approaches is the subject of ongoing research and debate. Their application to environmental and sustainability issues is still in its early stages. Nevertheless, it is possible to trace the roots of complex systems thinking and its application to environmental and evolutionary issues back to Georgescu-Roegen (1971) and Kapp (1970 [1974]), and significant progress has been made in recent years via the development of ecological economics that has done much to combine the analysis of ecosystems and economic systems (Costanza, 1989; Kirchner, 2003; Pitman, 2005; Straton, 2006; Foster, 2005, 2011; Baumgärtner and Quaas, 2010). One of the challenges facing the further development of research integrating economic and ecosystems is its interdisciplinary nature, drawing as it does on analysis from the natural and social sciences.

Working across such disciplinary boundaries is not easy (see, e.g., Hardin, 1998, p. 683); however, meeting this challenge would appear to be essential if we are to enhance our understanding of the social costs of economic activity, most especially environmental damage. Recent research grounded in a systems approach encompassing economic and ecological systems has brought insights that can enhance and enrich thinking and policy making on these issues, and offers significant potential. Perhaps a major area of achievement has been to highlight the limitations of an overreliance on market-based instruments to the exclusion of other policy measures, such as reform of governance structures, changes in shared norms and innovation strategies.

2.1 Complex systems thinking

As noted in the definition above, complexity economics seeks to draw on wider thinking on 'complex systems' by applying ideas of non-linear dynamics, heterogeneous agents, networks, emergence and evolution (see, e.g., Foster, 2005; Mitchell, 2009). Various authors have sought to apply some or all of these ideas to economic thinking. In a series of volumes from the Santa Fe Institute for Complex Systems, Brian Arthur and colleagues developed ideas of the economy as a 'complex adaptive system' (Anderson *et al.*, 1988; Arthur *et al.*, 1997; Blume and Durlauf, 2006). This line of thinking led particularly to the application of agent-based modelling to economic problems, as discussed in Section 3.2. Allen (2001) and Allen *et al.* (2007) developed models of firms interacting in economic markets, emphasising properties of self-organisation and adaptive learning. These strands of thinking all highlight the fact that individuals and firms, though lacking in perfect foresight, are able to learn and adapt over time, and typically interact through networks. Emergent patterns arise out of these micro-level behaviours and interactions, but these are only discernible at higher systems levels. Foster (2005) identifies the dissipative, evolutionary and structural irreversibility of complex economic systems as important properties, together with the possibility that systems exist as both holistic entities and components parts. It is the connections and interactions within and between systems that lead to the emergence of complexity (Foster, 2005). This property of complex systems is highly relevant to the study of environmental sustainability that requires analysis of the connections and interactions between economic and ecological or natural systems.

2.2 Evolutionary and institutional economics

The application of evolutionary thinking to economics was boosted by the seminal book by Nelson and Winter (1982), which argued that individuals and firms have 'bounded rationality' and so follow habits and routines, which evolve by a process of variation, selection and retention. Metcalfe (1997) developed this relation between evolutionary economic theory and the Schumpeterian idea of economic change occurring through periods of 'creative destruction'. Recently, Dopfer and Potts (2008) have sought to develop a general theory of economic evolution, based on interactions between agents and structures at micro, meso and macro levels. Beinhocker (2006) argues that economic evolution is able to explain the explosive non-linear creation of wealth, increasing levels of variety and complexity and spontaneous self-organisation. Institutional economics highlights the role of institutions or 'social rule systems' in both enabling and constraining the choices of individual economic actors (see, e.g., Vatn, 2005; for a summary of the literature, see Hodgson, 2001). Beinhocker (2011) has subsequently argued that economic evolution may be regarded as a special case of an 'evolution as computation' perspective, linking the application of ideas of generalised Darwinism (Hodgson and Knudsen, 2006A, 2006B, 2010) and self-organisation (Foster, 1997) to understanding change in socio-economic systems.

Economic evolution is thus argued to be strongly path dependent—i.e. 'history matters'—and technological and institutional systems may become 'locked-in', creating barriers to the adoption of more beneficial alternatives. Van den Bergh (2007) argues that greater attention should be paid to the application of evolutionary theory to environmental questions, not least in the context of system resilience, resource use, ecosystem management and growth, but also in relation to individual behaviour and environmental policy. Many of the limitations of neoclassical economics spring from the underlying model of rational choice or business decision making, with no meaningful analysis of the institutional environment in which business and policy decisions are taken. Ostrom (2006, 2007) provides significant insight into the use and evolution of governance systems to manage the commons and natural common pool resources; she found, empirically, that strategies for collective action evolve and adapt, aided by the design of appropriate institutions, thus enabling systems to escape the tragedy of the commons predicted by neoclassical economics. Similarly, Michie and Oughton (2011) show how alternative managerial, institutional and evolutionary theories provide richer insights into environmental problems and a broader spectrum of policy choices.

2.3 Ecological economics

Ecological economics highlights the dependence of human economic and industrial activity on the resources, waste assimilation capacities and ecosystem services provided by natural systems (see Costanza, 1989; Hardin, 1998; Common and Stagl, 2005; van den Bergh, 2007; Barker, 2011). The economy is seen as a large and growing subsystem of the biosphere. This suggests the need to develop approaches and models that integrate ecological and economic factors, rather than merely trying to 'internalise environmental externalities', as neoclassical economic thinking aims to do. Faber and Frenken (2009) suggest that complexity economics represents a third generation of evolutionary economic modelling, in which the evolution of natural systems is represented endogenously, as is technological and institutional evolution.

2.4 Social and psychological understanding of human behaviour

Recent social science research has generated a deeper understanding of the social and psychological drivers of human behaviour, particularly in relation to the consumption of goods and services (see, e.g., Dawnay and Shah, 2011; Thaler and Sunstein, 2008; Whitmarsh, 2011; Nye *et al.*, 2010). This implies that policies to reduce unnecessary consumption need to target multiple—not just economic—motivations and to change social and institutional structures to facilitate this.

2.5 Social–technical transitions

Research has examined how systems transitions can occur through interactions between social and technological elements (see, e.g., Grin *et al.*, 2010). A key element of this is how existing dominant regimes are challenged, both by wider changes in the cultural 'landscape' and through activities in technological or market 'niches'.

Thus, complexity economics is able to draw on a wide range of theoretical resources to address the key environmental and sustainability questions that face us currently, namely as follows:

(i) What are the mix of incentives needed to promote more sustainable patterns of behaviour by consumers and businesses?
(ii) How to promote technological and social innovation for sustainability, overcoming inertia and the lock-in of current technologies and institutions?
(iii) Can a transition to more sustainable patterns of production and consumption be achieved in ways that are compatible with ensuring a continuing spread of economic prosperity in both developed and developing countries?

3. Key tools and techniques

The approaches discussed above have been applied in a range of ways quite different from conventional economic environmental analysis, including systems analysis, agent-based modelling, input–output analysis, social network analysis, transitions analysis and coevolutionary approaches. Many of these are complementary and lessons can be transferred between them; together they enable the application of the ideas of complexity economics to current environmental and sustainability challenges.

3.1 Systems analysis

A fundamental aspect of this new thinking is the need for a more holistic approach. Systems analysis is now being extensively used to investigate the interactions between social, economic, technological and natural elements. As described in Section 2.1, many authors have argued that economies can be understood as 'complex adaptive systems', consisting of many interacting agents. However, most of these analyses ignore the fundamental ecological basis on which these systems depend. Economic systems transform energy inputs, typically in the form of fossil fuels and calories from agricultural production, into useful goods and services, which have high local order, at the expense of an overall increase in disorder or entropy, in the form of waste products, heat and greenhouse gases (Georgescu-Roegen, 1971).

Concepts of *sustainability* and *resilience* may be used to examine how dynamic systems can maintain and enhance the desirable properties of environmental integrity, social equity and human well-being under transient *shocks* and enduring *stresses*, both internal and external to the system (Smith and Stirling, 2010; Scoones *et al.*, 2007). Whilst *incumbent* institutions will favour strategies that seek to preserve the status quo, focusing on the maintenance of incumbent technologies, traditional practices, monopoly firms and dominant industrial sectors, other actors will often seek to pursue more radical strategies, involving engaging stakeholders, addressing multiple systems, exploring uncertainties, highlighting ambiguities and maintaining flexibility and diversity. This argument is further developed in transitions analysis. A strategy of promoting *diversity* is generally effective in promoting stability, resilience, durability and robustness of systems. For example, a more sustainable set of energy technologies will have greater diversity. This analysis needs to incorporate disparities between different renewable energy technologies, as well as differences between renewables, nuclear power, coal, oil and gas as primary fuels.

Ravetz (2009) argues for a dynamic and systems-based analysis of economic activity. This would involve relating physical supply chains both to resource use and waste generation, and to the economic and social value cycles in which they are embedded. It requires a relational approach, combining economic insights on investment and returns with social insights, such as trust and reciprocity, and institutional contexts. Key themes of a relational economy approach include the following:

(i) Economic flows, incentives and signals, focusing on the material exchange dimension.
(ii) Combining this with other dimensions—political, social and cultural.
(iii) To 're-socialise' the economy, we need links between these, both in theory and in practice and at micro and macro scales.
(iv) Revisiting key assumptions and paradigms to break down barriers, such as a rigid boundary between the concepts of production and consumption.

An example of the policy implications of this approach is the competing discourses around the proposed (and failed) introduction of congestion charging in the city of Manchester. Here, the claimed economic and environmental benefits of this scheme were defeated by arguments focusing on narrow views of economic costs and the strength of antigovernment feelings. Ravetz argues that a 'one planet transport' discourse incorporating wider social and economic changes between all types of stakeholders could have been more effective.

Simelton *et al.* (2009) present another example of the broader analysis implied by a systems approach, considering the challenge of adding some socio-economic perspectives to examining and anticipating global food security problems. Under the 'Quantifying and Understanding the Earth System' programme, they looked for key socio-economic indicators that have made harvests in China susceptible to drought. Examination of past droughts found cases of both resilience, in which major droughts led only to minor crop failures, and sensitivity, in which minor droughts have led to major crop failures. They then examine socio-economic factors that give rise to this increasing vulnerability. The objective is to use this work to create 'vulnerability maps' that will identify regions that are (1) likely to be exposed to drought and (2) unlikely to have the capacity to adapt. The generic lessons from this work are that scoping a problem down and taking a problem-oriented approach is a useful way forward.

3.2 Agent-based modelling

This approach to complexity has been incorporated into numerical modelling through agent-based models. Here, the idea is to model economic systems by modelling each agent (producer or consumer) individually. Instead of a rule for market equilibrium, there are rules for each agent's individual behaviour in response to the actions of other agents and the general environment. This is in contrast to the 'representative agent' concept of neoclassical economic models, where all agents are assumed to have the same behaviour. This means that agent-based models incorporate the ideas of complex systems. An important contribution was the work of Epstein and Axtell (1996), who were able with simple rules to develop a simulation where economic institutions such as banks emerged through differences in agents' resources and capabilities. This literature is reviewed in Chen and Wang (2011). Applications of agent-based modelling to environmental issues are surveyed in Heckbert *et al.* (2010). A more complex agent-based system simulation applying the ideas of transition theory to a transition to sustainable mobility is described in Köhler *et al.* (2009).

3.3 Input–output analysis

An important tool with a longer history in the economic literature is input–output analysis combined with emissions accounting. Guan *et al.* (2008) present an approach that combines 'bottom-up' life-cycle analysis of goods and services with 'top-down' input–output analysis at a country level. In contrast to the current producer basis for calculating CO_2 emissions, this shows that the UK's CO_2 emissions on a consumer basis have risen significantly since 1992, due to the embodied CO_2 emissions in imported goods from China and other countries. Despite efficiency improvements, China's production-related CO_2 emissions have risen by 59% from 1992 to 2002, mostly due to large increases from construction and other capital investments, and from urban household demand. In the UK, the largest increases in the carbon footprint from final demand have come from travel and recreation activities. As well as scientific challenges of uncertainty and data collection, this raises policy and regulatory challenges. Guan *et al.* (2008) argue for the need for a 'shadow consumption-based indicator' alongside official accounting and for national actors to operate outside of their 'territory', e.g. by the UK investing in reducing production emissions in China.

3.4 Social network analysis

In contrast, social network analysis is a new tool based on numerical data analysis. This uses 'identified' contacts between actors. Quantitative data can be used - for example, sales of a product at the individual transaction level. Or networks can be identified through, for example, interviews and qualitative analysis. Saavedra *et al.* (2009) give an example of how a social network of firms in the New York City garment industry remained stable for a long period, despite high rates of firm entry and exit at the micro level, before eventually collapsing. Another potential use of social network analysis is to investigate how technological or market niches grow through networks of actors with common interests and complementary expertise coming together, leading to increasing returns to scale and non-linear growth.

3.5 Transitions analysis

Transitions analysis is a relatively new approach in innovations studies and a recent survey is provided by Grin *et al.* (2010). It has developed from the strategic niche management literature and uses a 'multilevel perspective' developed by Kemp and Rip (1998), which encompasses three functional levels: 'niche', 'regime' and 'landscape'—with increasing structuration (Giddens, 1984) and coordination of activities, ranging from individual technologies and grassroots movements to larger scale social structures and institutions. It emphasises the interplay between these different levels:

(i) The meso level of the socio-technical *regime*, consisting of (a) networks of actors, (b) formal, normative and cognitive rules that guide the activities of actors, and (c) material and technical elements.
(ii) The macro level of the *landscape*, namely slow-changing factors that influence the variety of regimes, including, for example, cultural and normative values.
(iii) The micro level of *niches*, within which innovations emerge as experiments in relatively protected spaces, which play a critical role in shaping more sustainable socio-technical regimes (Grin *et al.*, 2010).

3.6 Coevolutionary approaches

Understanding and analysing transition pathways to a low-carbon economy requires a coevolutionary approach, combined with a multilevel framework, addressing interactions between macro, meso and micro levels. This approach draws on insights from three research areas: socio-technical transitions, technological innovation systems and evolutionary economics. This has been used to explain how the 'carbon lock-in' of current high-carbon energy systems arises through the coevolution of technologies and institutions, driven by path-dependent increasing returns to adoption (Unruh, 2000). Here, two evolving populations coevolve if, and only if, they both have a significant causal impact on each other's ability to persist, either by altering selection criteria or by changing the replicative capacity of individual entities. An approach combining insights from these three areas, based on the coevolution of *ecosystems*, *technologies*, *institutions*, *business strategies* and *user practices*, has roles for both agency and structure in causal influences and can link issues across macro, meso and micro levels (Foxon, 2011). New research is analysing the interaction of social and technological elements within potential transition pathways to a low-carbon energy system for the UK (Foxon *et al.*, 2010). This is examining pathways with different roles for government, market actors and civil society, and different mixes of centralised and distributed electricity generation.

3.7 Complex systems: the interaction and evolution of economic and ecosystems

The development of complex systems theory and its application to economic and environmental questions has begun to challenge conventional economic thinking and its reliance on constrained optimisation techniques applied to simple, closed systems, often in a static context. As Foster (2005) has noted, part of the challenge is to recognise the complexity that derives from dissipative structures with heterogeneous agents that interact following rules which may evolve over time, resulting in an evolutionary process of change. A further challenge set out by Kapp (1970 [1974]) is to explore the 'interaction of several complex systems (economic, physical, meteorological, biological, etc) in which a plurality of factors interplay through "feedback processes"—an interaction which is much more complex and much less explored and understood than the functioning of the various systems which the conventional social disciplines have ever studied' (1970 [1974], pp. 85–6).

Although this research programme is relatively new, the set of tools and techniques reviewed above shows how interaction between complex economic systems and ecosystems may be analysed, yielding empirical results and policy conclusions that go beyond the treatment of environmental problems as externalities that may be resolved purely via a price mechanism. Rather, environmental questions are a central part of economic and ecosystems, and their solution requires an understanding of the dynamic properties of systems interaction. In the following section we consider how some of these tools and techniques have been applied to the question of economic growth and sustainability.

4. Compatibility of economic growth and sustainability

A critical area of debate is the question of whether there is a 'double dividend'—the possibility of improved environmental performance while also contributing to economic growth. Beinhocker (2006) argues that an ongoing process of coevolution of physical technologies, social technologies (i.e. ways of coordinating human activities) and business plans underlies the creation of wealth in industrialised countries, but that this process is now under threat as the environmental impacts of economic activity are recognised. He argues that in order to achieve and spread this prosperity whilst respecting the limits imposed by our impacts on the planet's climate and ecosystems, the world needs to understand and apply the lessons from the last Industrial Revolution; better understand how to achieve a transition to a low-carbon economy with minimal impacts on welfare and growth; and find the points of policy leverage for achieving the necessary 'social engineering' on a massive scale, whilst respecting individuals' free choices.

Applying insights from complex systems analysis can enhance our understanding of how to balance growth and sustainability. The existence of increasing returns and non-linearities in costs means that consumers and producers may become locked-in to existing technologies and established products as increasing returns to scale and associated barriers to entry keep more efficient, greener technologies out of the market place. Toyota faced this dilemma in the car industry as it struggled to find a large enough market to make the costs of production of its hybrid fuel vehicle competitive. Regulation by the California Air Resources Board, most significantly its Zero Emissions Vehicle Programme (ZEV) announced in 1990 and the partial-ZEV programme introduced in 2005, provided a sufficient market size to allow Toyota to reach the tipping point with production of its hybrid engine vehicle (Whitmarsh *et al.*, 2008). This policy had the effect of stimulating innovation with consequent knock-on effects as manufacturers of petrol-engine cars strived to match the hybrid's fuel efficiency. Similar applications of complex systems ideas are relevant for the analysis of energy transitions and the coevolution of the economic and ecosystem.

4.1 Learning from historical energy transitions

Fouquet and Pearson (2006) argue that energy systems are complex evolving entities and transitions involve interactions between fuels and energy-converting technologies, infrastructures, institutions, policy regimes, economic variables, environment and resources, and people. Britain's first Industrial Revolution from the sixteenth to nineteenth centuries from a largely agricultural to a mainly industrial economy relied on using a fossil fuel stock (coal) for larger energy flows, which transformed growth and welfare. By 1650, half of the UK's final energy consumption came from coal, but the use of wood fuels took centuries to die out. Despite availability concerns, coal output and mining jobs did not peak until 1913. Economic historians such as Robert Allen have investigated the question of why the Industrial Revolution happened in Britain first. Allen has argued that the high wages and cheap energy and capital in Britain (compared with other countries) created a real return for labour-saving capital investments, such as steam engines, cotton mills and the substitution of coal/coke for wood in metal manufacturing (Allen, 2009). Fouquet and Pearson (2006) show a negative correlation between energy prices and energy intensity (E/GDP) over five centuries. Successive technological substitutions have seen the cost of lighting fall to 1/3,000 of its value in 1800 by 2000, leading to a 6,500-fold increase in lighting use per capita, with high welfare benefits. So, a long-term perspective suggests that new technology diffusion takes time and that major productivity benefits of new technologies, such as steam engines or electric lights, were only observable decades after they were first introduced (Fouquet, 2008, 2010). Past transitions were not managed and modern transitions could be faster, but it still takes time to build new enthusiasm, infrastructure and institutions; to escape the shackles of path dependence; and to overcome 'lock-in' and turn over old capital stock (Pearson, 2009).

Overall, the conclusion from the historical evidence is that major breakthroughs do affect aggregate productivity growth, but only slowly over a period of decades. It is important to recognise the complex interdependencies involved between technologies, institutions and users. The importance of relative prices between wages and resources in past transitions also has implications for the relative prices and availability of physical and human resources needed to drive risky low-carbon innovation.

Other strands of work have sought to examine and quantify the contribution of energy sources to economic growth. As is well known, Solow (1956, 1957) showed that historical trends in economic growth cannot be explained in terms of capital and labour inputs alone, but require a residual term, which he interpreted as the contribution from autonomous technological change. Recently, Ayres and Warr (2005, 2009) argued that this is better explained by incorporating a function of energy delivered as useful work. They argue that technical progress, as defined by the Solow residual, is almost entirely explained by historical improvements in the useful work delivered from energy sources. The primary energy sources over the last century have been fossil fuels—coal, oil and gas. As these sources are now likely to become more expensive, as they become physically scarcer and economically penalised to enable the development of low-carbon alternatives, this suggests that we cannot automatically assume the continuation of past trends in economic growth into the future (Foxon and Steinberger, 2011).

4.2 Reconciling economic growth and environmental sustainability

Paul Ekins (2009) emphasises the importance of distinguishing between three types of growth:

(i) Physical growth: growth in the amount of matter and energy mobilised by the economy—indefinite growth of this kind is impossible in a finite physical system.
(ii) Economic (GDP) growth: growth in money flows, incomes, value added and expenditure—there is no theoretical limit on this kind of growth.

(iii) Growth in human welfare: this is dependent on sustaining environmental functions, has a complex relationship to economic growth (though, *ceteris paribus*, more money is better than less) and is dependent on many other factors (employment, working conditions, leisure inequality/income distribution, relationships and the security/safety of the future).

Environmental sustainability depends on the maintenance of important environmental functions and the natural capital these functions depend on. An aspiration for sustainable economic growth must recognise the need for the sustainable use of resources and ecosystems and be rooted in the laws of thermodynamics. Conventional analyses that relate output growth to a weighted average of growth in factor inputs (including energy) and a residual factor attributed to knowledge are too simplistic; Potts *et al.* (2010) and Foster (2011) have argued that growth processes are more complex, with economic and environmental systems coevolving.

To achieve a stabilisation of atmospheric concentration of CO_2 at 450 ppm, assuming ongoing economic and population growth, would need an improvement in carbon productivity (GDP/carbon emissions) by a factor of 10–15 by 2050. This 10-fold improvement in carbon productivity in 40 years contrasts with the 125 years the USA took to achieve the same improvement in labour productivity and would be very hard to achieve within a system in which firms still have a strong incentive to improve labour productivity (Ekins, 2009). So while sustainable, green growth is technologically and economically feasible, it would require sustained, wide-ranging and radical policy interventions to bring about technological revolution and change lifestyles (see Stern, 2007). These interventions would be resisted by affected economic sectors (e.g. energy) and households who want to keep current lifestyles (e.g. transport) or attain Western lifestyles. To ensure that growth is not pursued regardless of its economic and social costs, interaction between economic activity and appropriate energy pricing/use requires collective as well as individual action, involving economic variables such as energy prices as well as behavioural variables such as the emergence, acceptance and evolution of social norms (Foster, 2011).

4.3 A Green New Deal: climate change mitigation as an economic stimulus

There are strong reasons to think that climate change mitigation can act as an economic stimulus, as argued in the context of energy by Grubb *et al.* (2002). Bowen *et al.* (2009) also argue that there are a number of benefits to early climate-change mitigation action, as it:

(i) induces innovation sooner (by enabling learning, scale and network effects);
(ii) recognises that diffusion of new technologies takes time;
(iii) encourages action by establishing a credible policy framework sooner;
(iv) reduces the need for premature scrapping of capital;
(v) enables action to be strengthened if climate change proves more serious; and
(vi) provides greater benefits for win–win opportunities.

Recent modelling work suggests that the costs of stabilising at 450 CO_2 parts per million (ppm) would be up to 1.5% of GDP (Knopf *et al.*, 2009). The proponents of a Green New Deal argue that the current global downturn makes tackling market and policy failures easier, as there are lower opportunity costs (temporarily unemployed workers), scope for temporary public spending increases and potential for a boost to growth through fiscal stimulus. If policy measures are designed effectively, there may be higher benefit from spending on public goods under current conditions. Bowen *et al.* (2009) argued for a fiscal stimulus of 4% of global GDP, of which 20% or around $400 billion a year should be focused on a 'green' stimulus. In fact, over $512 billion or around 16% of total stimulus packages across industrialised countries were pledged, although over a number of years, rather than per year.

4.4 Prosperity without growth

A further important new direction is to reconsider the fundamental assumption of modern political economy—that economic growth is a necessary condition for the prosperity of society. Jackson (2009) outlines the arguments, focusing on the need for a new ecological macroeconomics. He begins by setting out the 'dilemma of growth'—that economic growth is unsustainable, at least in its current form, but 'de-growth' (the shrinking of the economy) is unstable because, under present conditions, it would lead to rising unemployment, falling competitiveness and continuing recession. He argues that only a relative decoupling of environmental impact from economic growth has so far been made. To achieve the target of keeping a global temperature rise to 2°C above pre-industrial levels would require a 130-fold improvement in carbon intensity to around 6 gCO_2/$ by 2050, for 9 billion people in the world to achieve an equitable income at around current European levels, assuming that industrialised economies continue to grow at 2% per annum, whilst other nations catch up. In the UK in recent years, growth has been driven by the pursuit of novelty-for-status consumption and increasing (labour) productivity, funded largely by personal debt, which has grown to over 100% of GDP, whilst the household savings ratio has dropped below zero. A different engine of growth is needed in order to retain economic stability whilst remaining within ecological limits.

This new engine of growth would be based on ecological investment delivered by ecological enterprise. Ecological investment would target renewable energy and the preservation of ecosystems and biodiversity, but would be likely to require lower rates of return over longer periods and changes to the ways in which productivity and profitability of investments are measured, to move away from a focus on GDP growth. This would be likely to require restructuring of financial markets and a greater role for the public sector. Ecological enterprise would focus on low-carbon, resource-light and/or non-material ways of meeting people's needs. These 'Cinderella economy' activities would be primarily service based and focused on providing jobs and supporting communities. These would not deliver high productivity growth, as conventionally measured, and so a structural shift would be required into more labour-intensive activities rather than high-labour productivity areas, in order to maintain jobs. In turn, this challenges the idea of a consumer society and implies the need to create an 'alternative' prosperity, based on social and psychological flourishing and the importance of participation. This would require building people's capabilities and investment in public goods and shared public spaces, which is in conflict with the prevailing values of the current economic system. The key message is that 'another world is possible', but that it would look quite different from the current world.[1]

In the last century, the world population grew 4-fold and per capita GDP grew 6-fold, leading to a 24-fold increase in the size of the global economy, from $2 trillion to $47 trillion. This means that the economy has expanded rapidly in the relation to the environment, which provides resource inputs and assimilation of wastes, with environmental impacts strongly correlated with GDP. So far, only relative, and not absolute, decoupling has been possible, e.g. from 1980 to 2005, GDP grew by 116% and material intensity reduced by 30%, meaning that total material use grew by 50%. A model for the Canadian economy by the ecological economist Peter Victor suggests that it is possible for an economy to have low levels of unemployment, poverty, debt-to-GDP ratio and GHG emissions whilst GDP per capita stabilises (Victor, 2008).

4.5 Moving beyond GDP

There is also an extensive literature criticising the current definition of economic activity, GDP and therefore the determinants of economic growth. Van den Bergh (2010) argues that economics is very confused about the direction of causality between GDP growth and things that we value, such as happiness, reducing environmental pollution, creating employment and technological progress. From a complexity perspective it is not necessary to understand the full extent of economic complexity; just sufficient insight is needed to design policies and remove barriers. These barriers include (hidden) subsidies, the preoccupation with growth, vested interests, lack of global government and free riding (collective action problem). The shortcomings of GDP as an indicator of social welfare or progress are well known amongst economists, but its role in economics, public policy, politics and society remains influential—this is the 'GDP paradox'.

Being against GDP is not the same as being against growth and Van den Bergh (2010) takes a neutral position on the need for growth. However, he argues that the goal of 'unconditional growth' is a constraint on the goal of improving human welfare, as it often frustrates good policy measures that would have direct benefits not measured by GDP. The growth aim is dominant politically and ignores informal activities, such as unpaid childcare. In particular, climate policy is frustrated by the goal of GDP growth, as economic cost–benefit analyses assume that less GDP growth is a cost. However, if GDP growth is 2% per year and the cost of climate policy ranges from US$1 to US$20 trillion (6% of total GDP over the period), then the delay time to reach a certain GDP level within about a century from now would be no more than three years. One solution is to use 'happiness' as an indicator instead of GDP.[2] It has been established that people's happiness or subjective well-being is delinked

[1] Keynes assumed that by 2030 we would be working 15-hour weeks; he also warned against overestimating the importance of economics or of 'sacrificing to its supposed necessities other matters of greater and more permanent significance' (Keynes, 1930 [1963], p. 373).

[2] An anonymous referee pointed out that happiness would only provide a better measure if it is responsive to moral responsibilities towards future generations. The difficulties of capturing such phenomena through surveys is discussed by Graham (2011), who also acknowledges that policies to increase aggregate welfare in the long term do not bring happiness to mind in the short term, at least (Graham, 2011, pp. 25–6).

from GDP growth above a certain threshold income (O'Neill, 2009). This leads to the hypothesis that climate policy will be less costly in happiness terms than in GDP terms. Similarly, the main concern of economic 'crisis' policy should be reducing unemployment, as this has tremendous happiness effects. So, an important challenge for economics is to discover how we can get full employment without the constraint of continuous growth. More work and employment may increase GDP, but this does not imply the reverse causality.

To summarise, there are several fundamental criticisms of the conventional environmental economic analysis of climate mitigation policy. In a dynamic analysis with increasing returns to scale through learning by doing and economies of scale in new technologies, there will be opportunities for increased economic activity in new mitigation technologies. More radically, there are many proposals for how to reorient society and economic activity, such that human needs are satisfied without requiring (conventional) economic growth.

5. Conclusion

Complexity economics represents an ongoing research programme, rather than a completed theory. However, some common threads are emerging, which have implications for policy to address the current environmental and sustainability challenges, including climate change, and the impacts of current consumption levels on resource extraction and waste generation.

The key insights from complex systems thinking are that economies are open, *dynamic* systems, not in equilibrium, and are made up of diverse *agents* who lack perfect foresight, but who are able to learn and adapt over time. These agents interact through various social *networks* and macro patterns *emerge* from these micro behaviours and interactions. *Evolutionary* processes create novelty and growing order and complexity over time. Other strands of social and ecological economic thinking emphasise that economic activity is embedded both in the ecological systems on which it depends and in the social systems within which it occurs. A unifying theoretical core identified independently by Costanza (1989), Hardin (1998) and Foster (2005) is that complex systems exist both as whole systems and as part of a wider system, interacting and overlapping. Hence, the ecosystem and the economic system coexist, interact and coevolve over time. Complexity economics, ecological economics and research on sustainability provide a unifying framework for the study of environmental questions. Such a framework is well suited to the analysis of the coevolution of physical technologies, social technologies (i.e. ways of coordinating human activities) and economic/business plans that underlies the creation of wealth in industrialised countries, and to the coevolutionary processes that have contributed to the lock-in of current high-carbon technological and institutional systems, inhibiting the adoption of low-carbon alternatives.[3] The dynamic, systemic nature of long-term industrial change highlights the fact that learning, scale, adaptation and network effects can give rise to increasing returns or positive feedbacks in the adoption of new technologies and institutions, so that the more they are adopted, the more likely they are to be further adopted.

[3] On the role that both policy and 'recombinant' technologies can play in preventing lock-in to dirty technologies, see Zeppini and van den Bergh (2011).

The general policy implications of this approach are as follows:

(i) Complexity economics provides a rich understanding of the behaviour of economic actors and systems, which environmental and sustainability policy would benefit from taking into account.
(ii) This is particularly relevant for policy aiming to contribute to a transition to a sustainable low-carbon economy: support for technological or market niches may be important to enable the innovation and deployment of low-carbon alternatives.
(iii) Tools such as systems analysis, input–output analysis, social network analysis and coevolutionary approaches, together with new economic thinking, can be used to better understanding economic processes and systems.
(iv) Policy needs to understand and address the drivers of consumption, as well as production: social and psychological understanding of the behaviour of individuals and the influence of the social context on behaviour can inform an understanding of the drivers of consumption and how these can best be influenced.
(v) New measures of the social and ecological value of economic activity need to be explored, to go beyond a reliance on aggregate indicators such as GDP.[4]

Beinhocker (2006) argues that to achieve the necessary dramatic improvements in carbon productivity, carbon price is necessary, but far from sufficient; innovations in social technologies will be critical, including new regulatory frameworks, new market structures, new business forms and new international institutions. Also, we need to think broadly—e.g. about female education in developing countries, green technology innovation clusters, catalysing infrastructure investments and changing cultural norms.

Barker (2011) advocates just such thinking, through an 'earth systems' or 'whole systems' approach to ecological economics, based on an understanding that the behaviour of the system cannot be understood adequately by focusing on the behaviour of its individual components alone: interaction between components leads to outcomes at the system level that differ, in some cases diametrically, from the behaviour of individual components. Likewise, Corning (2002) argues for the importance of transitions in economic systems, just as Maynard Smith (1989) had done as regards human evolution. This involves the need to understand and appreciate: firstly, that complex systems are more than the sum or their parts; secondly, that economic policy cannot work just on the margins, but needs to also tackle the whole system; and thirdly, that such analysis and policy work needs to be applied to periods of transition in economic systems.

The policy proposals from Jackson (2009) draw together a wide range of social, ecological and economic research, arguing the need to:

(i) *Establish the limits*
- Establishing clearly defined resource/emissions caps.
- Fiscal reform for sustainability.
- Promoting technology transfer and ecosystem protection.

(ii) *Fix the economics*
- Developing the macroeconomics of sustainability.

[4] On the slightly different point, of what a 'complex systems approach' to the value of ecological resources would be, see Straton (2006).

- Investing in public assets and infrastructures.
- Increasing financial and fiscal prudence.
- Improving macroeconomic accounting.

(iii) *Change the social logic*

- Sharing the work and improving the work–life balance.
- Tackling systemic inequality.
- Measuring capabilities and flourishing.
- Strengthening human and social capital.
- Reversing the culture of consumerism.

The fact that a whole *range* of measures should be pursued, and that economic incentives on their own are insufficient, is supported by Kemp and Rotmans (2001, p. 55), who also point to the need to bring about structural change in a 'stepwise' manner (p. 54). Further research can help to demonstrate the likely effectiveness and efficiency of such policy proposals, but crucially, experience needs to be gained from the practical application of such policies, e.g. in particular market or local niches, to also inform their wider social and political acceptability. In pursuing such a policy agenda, it is important to avoid the restrictions of neoclassical assumptions and analyse real-world economic processes as they actually function and behave—in all their complexity.

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