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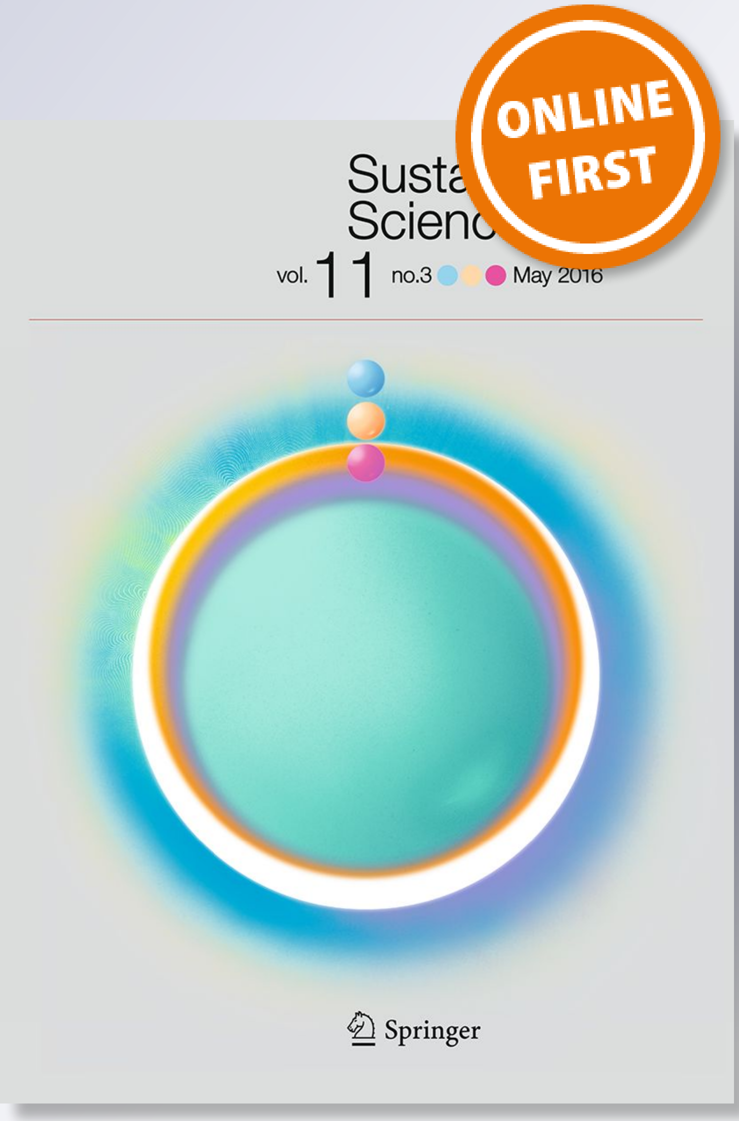

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OVERVIEW ARTICLE

Circles, spirals, pyramids and cubes: why the circular economy cannot work

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Abstract The concept of a circular economy has become a significant school of thought in sustainable economics over the last 10 years. This paper critically analyses the key principles underpinning the concept of the circular economy, specifically examining the thermodynamic and ecological foundations upon which these principles are apparently rooted. We examine issues related to recycling, biological and technical nutrients, restoration, energy use, elimination of waste, eco-efficiency, product lifetime and economic growth under three headings: the pyramid of waste, short cycles and eco-inefficiency. We reflect on how the economy of nature is based on an open system, not a closed system, that nature operates using short cycles, not extended lifetimes, that nature is sub-optimal, not optimal and that nature is eco-inefficient, not eco-efficient. Findings are then discussed, and we explore what we can learn from the natural world in terms of sustainability.

Keywords Bio-participation · Closed loop economy · Cradle-to-cradle · Sustainability · Sustainable economics · Thermodynamics · Biomimicry · Spaceship Earth

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Introduction

A circular economy: definitions and foundations

Over recent years, the concept of a circular economy has become a significant school of thought within sustainable economics (Murray et al. 2017). Championed by the Chinese government, and integrated into its 5-year plans over three cycles, Europe has also begun referencing it as a major set of policies. According to the definition in the Law to Promote Circular Economy in the People's Republic of China, the circular economy is the integration of activities of reduction, reuse and recycling during production, exchange and consumption (Shen and Qi 2012).

The Ellen MacArthur Foundation defines the circular economy as an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, moves towards the use of renewable energy, eliminates the use of toxic chemicals which impair reuse and aims for the elimination of waste through the superior design of materials, products, systems and, within this, business models (EMF 2012). Other authors also observe that the circular economy is not merely a preventative approach, reducing pollution, but also aims to repair previous damage (Cooper 1999; Nakajima 2000).

The concept of a circular economy is an essential component of the resource efficiency initiative of the EU2020 strategy. The EU has written that: "In a world with growing pressures on resources and the environment, the EU has no choice but to go for the transition to a resource-efficient and ultimately regenerative circular economy" (EU 2012, p 1). Differences between the Chinese and European interpretations of a circular economy are discussed in Skene and Murray (2015).

Europe, along with nations around the world, has agreed the 10-year Framework of Programmes on Sustainable Consumption and Production (10YFP) at the Rio+20 Conference, emphasizing circular economy-like principles (Tukker et al. 2008). UNEP developed its definition of the circular economy as featuring low consumption of energy, low emission of pollutants and high efficiency, using it as a generic term for an industrial economy which is, by design or intention, restorative. The aims are to 'design out' waste, to return nutrients and to recycle durables, using renewable energy to power the economy (UNEP 2006).

Ghisellini et al. (2016) observe that in China, the circular economy is promoted as a top-down national political objective and has been installed as its overarching environmental policy, while in the European Union, the USA and Japan, it is a tool to design bottom-up environmental change. However, this is changing rapidly as can be seen in recent circular economy literature. For example, the recent paper by the Ellen MacArthur Foundation (EMF 2015), entitled Growth Within: A Circular Economy Vision for a Competitive Europe, targets a political, top-down, transnational engagement. Proponents of the circular economy model clearly see it as displacing current approaches, and as the preferred suite of templates to deliver a sustainable future.

The circular economy is viewed as a better alternative to the dominant economic development model (Ness 2008). The EMF has set out to sign up large multinational companies to its concept of a circular economy and clearly sets out to put the circular economy forward as the fundamental set of economic policies at local, national and global levels (EMF 2012, 2013, 2014, 2015). Ghisellini et al. (2016) p 2 embraces the circular economy as the transcendent approach, stating that the "circular economy contributes positively to reconcile all the elements, thanks to its underlying rationale, mainly rooted in environmental and political as well as economic and business aspects". Moriguchi (2007) claims that the circular economy is a grand harmonization between industrialization and its natural limits. It is described as a business model, a system and a mode (Wu 2005; Zhijun and Nailing 2007; EMF 2012) and has been applied across a wide number of fields including agriculture, design, recycling and product service systems (Skene and Murray 2015; Murray et al. 2017). Heshmati (2015, p 5) claims that "The circular economy presents a unique policy strategy for avoiding resource depletion, energy conservation, waste reduction, land management and integrated water resources management".

According to Baily et al (2013), the circular economy is built on four principles: designing products with their entire life cycles in mind; maximizing product life cycles; recycling materials from end-of-life products; and reusing materials across diverse industries and value chains. Bakker et al. (2014) and Bocken et al. (2016) further develop these ideas.

The core foundations of the circular economy are as follows: recycling (Shen and Qi 2012; Baily et al. 2013); restoration (Cooper 1999; UNEP 2006; EMF 2012; EU 2012; Nakajima 2000); renewable energy use (UNEP 2006; EMF 2012; Preston 2012); elimination of waste (UNEP 2006; Shen and Qi 2012); elimination of toxic chemicals (EMF 2012); eco-efficiency (Schmidheiny 1992; Von Weizsäcker et al. 1997; UNEP 2006; EU 2012); biological nutrient return (UNEP 2006); extended product life (Boulding 1966; Schmidheiny 1992; Stahel 1998; Preston 2012; Baily et al. 2013); and economic growth (Schmidheiny 1992; EMF 2012; Stahel 1998).

Origins of the circular economy

In terms of the circular economy, the concept can be seen to have emerged from established sustainable economics thinking, including such schools of thought as industrial ecology (Frosch and Gallopoulos 1989; Allenby 1998), industrial symbiosis (Babbage 1835 p 217; Ayres and Simonis 1994; Chertow 2007), biomimicry (Merrill 1982; Benyus 2002), Cradle-to-Cradle (McDonough and Braungart 2002), eco-efficiency (Schaltegger and Sturm 1989; Schmidheiny 1992) and waste-is-food (Babbage 1835 p 217; Andersen 2007; Sherwin 2013). Skene and Murray (2015) trace the genealogy of current schools of sustainable thinking, exploring the historical lineages that have paved the way to the circular economy and similar concepts.

The waste-is-food concept lies at the heart of the circular economy and has its origins in the distant past. Underpinning industrial ecology, cradle-to-cradle, the circular economy, the closed loop economy and many of the other major schools of modern thinking, waste-is-food can be traced back to the beginnings of human civilization. Some of the oldest urban archaeological evidence of resource recovery comes from the late Stone Age city of Çatal Hüyük, in central Turkey. Bones left over from food were used in the manufacture of awls, punches, knives, scrapers, ladles, spoons, bows, belt hooks, pins and cosmetic sticks (Mellaart 1967).

As early as 1848, R.W. Hofmann, the first President of the Royal Society of Chemistry, stated "In an ideal chemical factory there is, strictly speaking, no waste but only products. The better a real factory makes use of its waste, the closer it gets to its ideal, the bigger is the profit" (in Lancaster 2002, p 10). The Danish writer, Peter Lund Simmonds observed that: "one of the greatest benefits that Science can confer on man is the rendering useful those substances which being the refuse of manufactures are either got rid of at great expense, or when allowed to decompose produce disease and death" (Simmonds 1862, p 10). Karl Marx went further, claiming that industrial waste recovery was “the second great branch of economies in the conditions of production”, the first being economies of scale (Marx 1909, p 120–121).

Greyson (2007) claims that Kenneth Boulding was the originator of the circular economy concept. Boulding (1966, p 7–8) wrote: “Man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy”. The term circular economy was first used in the Western literature in 1980s (Pearce and Turner 1990) to describe a closed system of economy–environment interactions. More bizarrely, in a brazenly revisionist swoop, Baily et al. (2013, p 10) accredit the McKinsey Global Institute for coining the term, stating “circular economy is another term coined by the McKinsey Global Institute”. There is no evidence of this elsewhere in the literature.

Recent literature has provided analysis of the application of circular economy thinking to agriculture (Song et al. 2014), design (Bakker et al. 2014), recycling (Prendeville et al. 2014; Sevignè-Itoiz et al. 2014) supply chain (Zhu et al. 2010), business models (Bocken et al. 2016) and product service systems (Tukker 2013). For a detailed review of the development of the concept of the circular economy, Hill (2015) and Ghisellini et al. (2016) should be referenced.

This paper critically analyses the key principles underpinning the concept of the circular economy, specifically examining the thermodynamic and ecological foundations upon which these principles are apparently rooted. We examine issues related to recycling, biological and technical nutrients, restoration, energy use, elimination of waste, eco-efficiency, product lifetime and economic growth under three headings: the pyramid of waste, short cycles and eco-inefficiency. Findings are then discussed, and we explore what we can learn from the natural world in terms of sustainability. Sustainability is defined as the maintenance of capital, be that economic, social or environmental capital. Strong sustainability states that natural capital must be protected at all costs and cannot be replaced with human-made capital. Weak sustainability seeks to maintain total capital from generation to generation, through substitution. Thus, if natural capital declines, provided that human-made capital increases by the same amount, then total capital will be maintained (Skene and Murray 2015).

Not only does this paper question the biological basis claimed for the principles underpinning the circular economy, but, further, it explores whether or not these principles are relevant to meeting the challenges facing the world at present.

Issues with the circular economy

The pyramid of waste

The Waste Directive 2008/98/EC of the European Parliament (EC 2008) states that “waste means any substance or object which the holder discards or intends or is required to discard”. In the National Standard of the Russian Federation, waste is defined as “residues of products or complementary products formed during or after certain activities and are not used in direct connection with this activity” (GOST R 53691-2009). Moniruzzaman et al. (2011) define waste as the unwanted matter coming from the production and consumption of materials by human and animal activities. Ezeah (2010) believes that any contemporary definition of waste is dependent on the nature and source of the waste, including its characteristics and/or the potential to cause harm either to humans or the environment.

However, these definitions of waste miss the most significant form of waste, which in reality dominates both economic and biological arenas, that of energetic waste. Energetic waste such as heat waste or eutrophication is here defined as any increase in energy flow through the Earth system as a result of human activity. Energetic waste is a particularly serious issue, leading to many devastating consequences for the biosphere, including de-oxygenation of water bodies. It is often ignored because energy is neither a substance nor an object, as referenced in most waste definitions. Ultimately, it is energy that forms the currency of life and business, and the flow of energy through both human and natural economics shapes and directs both spheres (Georgescu-Roegan 1971). Hence ignoring energetic waste is a strategy of doubtful value. Energetic waste fundamentally underpins the damage potential of human activity. While human energy use has led to a significant elevation of carbon dioxide in the atmosphere, it is not merely the use of energy by humans that creates issues, but rather the attempts by humans to increase energy flow through agricultural ecosystems, and the release of excessive fertilizer waste into natural ecosystems. Other energetic waste includes heat energy released in open loop cooling of thermonuclear power plants, where thermal plumes decrease the concentrations of dissolved oxygen in the receiving water and can cause significant changes to the ecosystems involved, decreasing biodiversity (McDonald et al. 2012; Madden et al. 2013). Thus, material that can be recycled is not without cost, since recycling involves huge associated energy waste. Embodied energy within recycling processes, often ignored operationally within the circular economy, with the exception of a few authors (e.g. Allwood et al. 2012; Allwood 2014), is a major waste issue.

The circular economy is based on the idea of a closed loop, where materials and energy cycle through the system, rather than a linear economy, where waste is continually generated, creating problems of waste management and resource depletion. This is thought to reflect how the natural world operates. However, in reality, nature's economy does not operate like this. Economists continue to use antiquated ecological theory and imaginary constructs of the planet far removed from real science (see Skene and Murray 2015, for a detailed exegesis on how antiquated science suffuses modern sustainability thinking). Modern ecological research recognizes significantly different underlying principles, including the fact that the Earth is an open system, not a closed system, that the biosphere is best understood using an emergent, complex system approach rather than adopting a reductionist approach, that function rather than form is central to any understanding of biosphere resilience and recovery, and that dynamic equilibrium or non-equilibrium models are preferred to a static equilibrium approach. While much of the work on the circular economy has emphasized a 'Homo habilis' approach, where we attempt to "fix" nature by intervention, other workers point to the importance of recognizing systems theory and concentrating on real-time, multi-dimensional monitoring, aimed at discovering what impact any change in human behaviour will have on the system (e.g. Moriguchi 2007; Rodrigues et al. 2016).

We can refer to this reliance on a static equilibrium model as the Garden of Eden fantasy. In this imaginary world, which is a closed system, the equilibrium can be restored by putting the pieces back in place through ecosystem restoration. Everything circulates eternally and balance is maintained as a climax community (Marsh 1965). Perpetual motion exists, and cycles continue, with no waste, a truly circular economy. Many circular economy protagonists emphasize the concept of zero waste as a central plank to the overall concept (e.g. UNEP 2006; EMF 2012; Preston 2012).

What better example for a human economy? Tight cycling, self-healing, waste-free, continually growing—an economist's paradise and an Enlightenment dream. Spaceship Earth (Boulding 1966) became the dominant metaphor. However, modern ecology recognizes that replacing forms will not restore the equilibrium. Rather, nature is dynamic and emergent, meaning that because of the countless interactions and pervading laws of thermodynamics, we cannot hope to restore an equilibrium state, even if it was warranted. Nature continuously changes, with forms replacing other forms constantly.

Although a few authors (e.g. Allwood et al. 2012; Allwood 2014) reference flow of materials through the economy, while Cooper (2005) emphasizes the sufficiency of resources, at a fundamental level, a circle is a circle, zero waste means zero waste and a closed loop is a closed loop. Thus, the terminology associated with the circular economy is clearly misrepresentative, re-enforcing the idea that nature can somehow inform a revolution in sustainable economics, because it is a closed, zero waste, circular system.

Yet nothing could be further from the truth. Referencing nature in any attempt to justify zero waste, eco-efficiency, optimization or circularity is, at best, misleading. Furthermore, sufficiency of resources cannot be considered as an isolated phenomenon, but must be assessed alongside energy flows. Energy flow poses the greatest threat to the planet in terms of sustainability (via eutrophication, climate destabilization and food web disruption). Without the flow of energy through the planet continuously, life would cease to exist, no matter if the material all remained on the planet. This is because natural recycling depends on energy-expensive processes, linked to reduction and oxidation processes. Without this energy, the biological cycles break down.

Earth is not a closed system nor is it a spaceship. Earth is an open system (Brillouin 1949). Our universe is a closed system, but all that lies within the universe must obey the second law of thermodynamics, which states that disorder (or molecular randomness) will increase within the closed system up to the point of maximum disorder and a temperature of absolute zero (Clausius 1867). The only reason we have increasing complexity on Earth at present is because of the increasing disorder in the Sun, which is slowly consuming itself, releasing vast amounts of radiation as it does so. Some of this radiation impacts the Earth, and a small fraction of this is converted into chemical energy. A tiny amount of radiation is also emitted from the core of the Earth which is still cooling following its formation and is released through hydrothermal vents and volcanic activity. However, any constructive activity on Earth always produces disorder. Indeed, in thermodynamic terms, complexity represents a means of producing disorder. Whether it is growth or maintenance, free energy is converted to waste.

Hence, the Earth as a whole is generating disorder, or waste, in accordance with the second law. This applies to both biological and technical cycles (Ulanowicz 1997; Kleidon and Lorenz 2004; Kleidon et al. 2010; Martyushev and Seleznev 2013). Lovelock (1965, p 568) observed that "Life is one member of the class of phenomena which are open or continuous reaction systems able to decrease their entropy at the expense of substances or energy taken in from the environment and subsequently rejected in a degraded form". As the biosphere becomes more complex, more energy is required and more waste is produced. Toussaint and Schneider (1998, p 3) state that "As biosystems grow and develop, they should increase their total dissipation [waste production]". Thus, complexity is an expected outcome of the second law, provided that adequate free energy is available (e.g. a neighbouring star). If energy is not supplied continuously from the Sun, then complexity is lost. Sixty-five million years ago, through a combination of dust ejected into the atmosphere from a colliding comet and a huge volcanic eruption (the Deccan Plains), sunlight was blocked from the Earth in what is called an impact winter (Retallack 1996; Yang and Ahrens 1998). The Earth was starved of free energy, with calculations indicating that solar transmission was reduced to 10–20% of normal for a period of 8–13 years, producing a decade of freezing and near-freezing temperatures (Pope et al. 1994).

Thus, Earth is not a closed system or an air-tight spaceship, as imagined by Boulding (1966). Instead it is an open system, reliant on a huge river of energy flowing through it. Cut off the energy supply and the whole thing collapses. If we were to base our economy on a natural model, we would have to imagine billions of tons of gold continually being sent down to Earth from some philanthropic alien every day. Nature is a dependent economy, hooked on sunlight. The only way to reduce waste production is by reducing complexity (de Man and Friege 2016). Easily said, but the reality of this would be extremely unpleasant for the human race. A zero waste economy would require zero complexity.

Some advocates of the circular economy promote the concept of holonic distribution (Christensen 1994; Lin and Solberg 1994; Gwamuri et al. 2014), defined as "a new pattern of interfirm relationships evolving network-wide integration by creating different forms of inter-entity processes" (Kühnle 2010, p 2). Advocates of distributed manufacturing promise potential benefits over centralized manufacturing, including reduction in production waste, maximization of material use efficiency and a contribution to rural community wealth creation in the developing world (Gwamuri et al. 2014).

The atom economy, as developed in the green chemistry approach (Anastas and Warner 1998), focuses on recycling individual elements, but given the complexity of many alloys and polymers utilized in manufacturing, the energetic costs, the associated chemistry and the diverse geo-economic contexts within which the waste material is generated, this is at present a difficult concept to follow.

In terms of recycling, another central theme in the circular economy, materials are degraded during this process and require energy to restore them (e.g. through the oxidation/reduction cycle). But crucially, recycling creates yet more waste. Wear and tear are unavoidable consequences of use within an entropic universe. Prevention of degradation requires less recyclable materials, which means that greater energetic cost is incurred in recycling. Thus, maintenance is required just to stand still. This is an important point. For an economy to grow [and remember, thermodynamics applies equally to human economic activity as it does to cosmic events (Georgescu-Roegan 1971)] not only must energy be degraded to achieve the growth, but energy must also be degraded to maintain all of the previous growth. Over time, energy use continues to rise since the estate requiring maintenance must increase if growth >0. Even at zero growth or de-growth, a large amount of estate previously grown still requires maintenance.

Meadows et al. (1992) emphasize that a sustainable society must emphasize sufficiency. Daly (1996) pointed to a need to move to a steady-state economy, but emphasized that this could not represent a circular economy because of thermodynamic considerations (Daly 1977). Princen (2005) also advocates sufficiency. Lamberton (2005, p 53) highlights the problem that exists between a growth-based economic model and the need to reduce material use, writing: "the sustainable sufficiency concept reinforces the view that neoclassical economic principles provide a barrier to achieving the social and ecological objectives contained within contemporary interpretations of sustainable development." While the circular economy attempts to dematerialize growth, it also relies on an economic model that has been set out to maintain the neoclassical economic principles so beloved of the dominant advocates of globalization, of which growth is an inherent necessity (Skene and Murray 2015).

Food pyramids are a clear demonstration that waste dominates the biosphere. Figure 1 represents the difference between the natural world and the circular economic interpretation. In nature, significant inefficiency exists, wherein 90% of energy is lost at each trophic level, meaning that a small number of top consumers, such as humans, require major primary and secondary productivity to sustain them. Hence, the energy flow through ecosystems diminishes with each level of consumption, with waste energy far outweighing useful energy at each stage. Thus, the tropic pyramid tapers sharply. The Garden of Eden fantasy, as employed by the circular economy, portrays nature as a perfect cube, where no waste occurs. This is simply incorrect. Furthermore, these pyramids are actually inverted, with humans at the bottom. We rely on the trickle-down effect, with energy passing from the Sun to photosynthetic organisms and then through numerous animals before reaching us. This makes us extremely vulnerable to the functioning biosphere above us, whose very operation is threatened by our activities.

Also, it does not matter whether the energy is green, blue or black, disorder will still increase, requiring further energy. Green energy will not deliver any form of solution. The only way forward is to reduce energy expenditure and

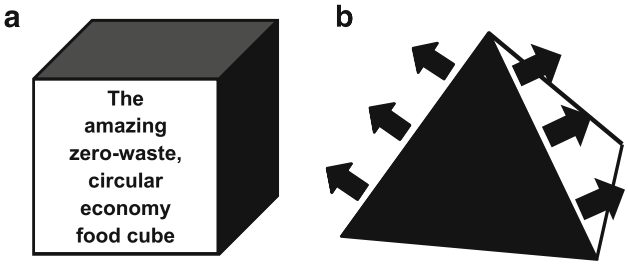

Fig. 1 Circular economy and ecological reality. **a** The circular economy, like many other schools of sustainability, strives for zero waste. In this rationale, a food chain would be a cube, with no waste. **b** A real ecosystem has a food chain that is a pyramid, with 90% loss of biomass at each stage, supporting fewer and fewer organisms. The peak predators are few in number and are reliant on the levels below for the energy needed. Waste of biomass and energy is de rigueur in the real natural world From Skene and Murray (2015)

this can only be achieved through de-growth. This is why we reach asymptotes, or ceilings in nature, be it in population size, organismal development, ecological succession or evolutionary diversification (Skene 2013). There is a maximum amount of disorder that can be produced at any level of organization, beyond which the system would collapse. This is called the maximum entropy production principle (MEPP), where "non-equilibrium thermodynamic systems are organized in steady state such that the rate of entropy production is maximized" (Kleidon et al. 2010, p 1298). Unless an asymptote is recognized and put in place early enough, production of disorder will not only increase the need for more free energy for maintenance, but the disorder will eventually destabilize the entire system. This can be seen in a lake where fertilizers applied in excess to surrounding agricultural fields drain into the water body. Fertilizers function by increasing productivity of crops, allowing more solar energy to be converted into chemical energy (sugar). However, in the lake, the fertilizers have the same effect, massively increasing primary productivity in algae. When the algae die, increasingly large bacterial populations break them down, consuming vast amounts of oxygen in a highly energetically wasteful process, and destabilizing the entire ecosystem. Fish die and bacterial toxins increase, leaving the lake all but dead. The fertilizers removed the asymptote formerly limiting productivity, leading to the demise of the ecosystem as excessive energetic flow destabilized the system.

The circular economy seeks to maintain an economy based on growth, energy use and technology, avoiding the need to challenge the incumbent economic system. However, sustainability must embrace social, economic and environmental issues and each of these components must contribute positively to the others. The circular economy merely tinkers with the current modus operandi, whereas this can never deliver an economic model that allows for environmental and social sustainability. Circles are not spirals, and for growth to occur, spirals with ever-increasing radii are required. Furthermore, spirals of economic growth create equivalent spirals of environmental damage.

Short cycles, not extended lifetime

Another central theme in circular economy thinking is the idea of extended lifetimes. Walter Stahel's concept of improved durability was drawn directly from Boulding (1966, p 12) who wrote: "I suspect that we have underestimated, even in our spendthrift society, the gains of increased durability". Stahel (1998) emphasized that long-lived goods and service-for-life extension combine to close material loops and reduce the speed of the resource flow, through prolonged utilization of goods. Furthermore, Stahel suggests that this increased service sector would bring economic growth. This becomes economically problematic at the level of geography. Many of the products utilized in Europe are made in Asia. If we reduce demand for these goods and increase the service sector to prolong the life of these products, then the economic benefits (increased employment in the service sector) will rest in Europe, whereas the economic costs (reduced sales and employment in the manufacturing sector) will occur in Asia.

The concept of 'product as service', where a product is owned by the supplier and the customer rents the use of the product, is emphasized by some circular economy thinkers (see Goedkoop et al. 1999; Mont 2002). Product–service system approaches can create benefits for struggling companies in terms of allowing the supplier to mitigate the effects of labour costs, leverage any advantages in competencies and in many cases strengthen the relationship with the customer (Aurich et al. 2010; Andersen et al. 2013). The consumption of scarce resources and environmental degradation can also be minimized through collaborative consumption (Baines et al. 2007; Piscicelli et al. 2015), although environmental benefits are not guaranteed, as seen in car sharing programmes, and requires careful monitoring (Pigosso and McAloone 2016). However, the servicing engineers require transport, replacement parts, longer-lasting materials, service centres and a large support network globally, all amounting to significant financial and environmental costs. Furthermore, as mentioned above, manufacturing rarely occurs in the same locality as sales, recycling and servicing, meaning that any benefits are likely to be externalized.

There is also the challenge of whether a greater environmental benefit is achieved through extending the lifetime of the product, rather than replacing it with a new, more energy-efficient model. Comparisons relating to virtual water (Allan 1998) and embodied energy (Costanza

1980; Miró et al. 2015) are required in order to assess properly how beneficial extended lifetimes really are relative to faster turnover. Fundamentally, ecosystem functioning [i.e. the combined study of solar energy flow, mineral cycling, water cycling and ecological succession (see Loreau et al. 2001)] is the only way to test the overall impact of this and any other approach, and so system-based studies must be carried out, rather than reductive laboratory studies (Skene and Murray 2015). Given that nature is an emergent system, it is only at the ecosystem level that the true impact of production choices can be assessed and thus ecosystem level indicators are central to any such analysis.

Yet again, nature does not follow the circular economy script here. In fact, the long cycle is eschewed in the biosphere. We find that fast cycling is the most common approach (Vogt et al. 1986). Material is quickly recycled for immediate use in most cases. Soils are particularly good at this. In rainforests, soil is shallow (10–15 cm deep), yet huge amounts of material rapidly flow through it (Vitousek and Sanford 1986). This is important otherwise these nutrients would be washed away in the large volumes of rainwater (Likens et al. 1970).

Speed is of the essence. Fast turnover is also observed in coral reefs and many other ecosystems. This is why eutrophication (the leakage of fertilizers from agricultural fields into natural ecosystems) has such a rapid and devastating effect (Jessen et al. 2013). Rapid recycling leaves natural systems extremely vulnerable to change in energy flow, a direct impact of fertilizers (which, after all, are designed to increase energy flow in agricultural systems). The key truth is that the biosphere has existed on a limited set of nutrients until recent times and has evolved to recover and circulate them rapidly.

We often consider resources to be of two types: technical (i.e. synthetic materials not normally found in the biosphere, such as plastics) and biological nutrients (produced by, cycling within and consumed by living organisms). However, when this material, either biological or technical, is inherently toxic or toxic at unnatural levels, the biosphere suffers. So not only do we need to try to avoid releasing technical nutrients into the environment, but the release of biological nutrients must also be carefully done so as not to exceed the appropriate levels (Reijnders 2008). The circular economy emphasizes recycling of biological nutrients, but if this is not done carefully, at a tempo in resonance with the natural order, it will seriously disrupt our ecosystems. Tempo is particularly significant in seasonal latitudes, because the addition of biological nutrients at different times of the year will have significantly different impacts (Rheuban et al. 2014).

Another circular economy mantra stresses the need for renewable energy. Yet the jolly green giant of renewable energy, while low in carbon, casts its own shadow upon the biosphere. Rare earth metals, central to wind power, require complex and toxic processes to release and concentrate them from their source materials (Li et al. 2013), but their chemistry makes them irreplaceable in terms of alternatives (Skene and Murray 2015). Solar panel production also produces significant pollution (Jacobs 2011). Palm oil production has devastating impacts on habitats (Mukherjee and Sovacool 2014). Many renewable energy approaches also use huge vast amounts of water (Dominguez-Faus et al. 2009). Thus, renewable energy may not be as green as generally perceived, and since it forms a central part of the circular economy, this is concerning. To be low on carbon dioxide production does not mean it is ecologically sustainable.

Excessive energy use is a signature of the current human condition and underpins much of the environmental damage that we have delivered. Thus, an emphasis upon the reduction in energy use, rather than the use of alternative energy sources, must be prioritized, while full ecological analysis is needed in order for consumers to understand the ecological impact of alternative energy sources.

One interesting application of energetics is in the field of sustainable transitions. The Viennese school of social ecology proposes the use of socio-metabolic profiling, focusing on resource use within social structures and exploring how these structures correspond to human modes of subsistence. According to the Viennese approach, the key to a transition is a society's energy system or metabolism. Major changes in socio-metabolic profiles were characterized by substantial increases in metabolic rates, corresponding, in turn, to substantial increases in entropic output (Fischer-Kowalski and Rotmans 2009; Haberl et al. 2011, 2016).

Eco-inefficiency, not eco-efficiency

Another central tenet of circular economy thinking is that nature is extremely efficient, and that by increasing efficiency we can attain greater sustainability. Eco-efficiency is defined as a reduction in material intensity, a reduction in energy intensity, reduced dispersion of toxins, improved recyclability, maximum use of renewable resources, greater durability and increased service intensity (Schmidheiny 1992).

Problems arise with this approach. As we have noted, nature is extremely wasteful, converting low entropy resources into high entropy waste, which requires vast amounts of energy to recycle, and, in turn, produces further high entropy waste. Nature has high energy intensity and it does not generally work towards greater durability, but, rather, fast recycling.

Eco-efficiency flies in the face of modern ecological knowledge. The biosphere is a system, made up of a number of subsystems, each working sub-optimally for the overall functioning of the system. System theory demands this, and we see it throughout the natural world (Skene 2011). Squirrels do not remember where they hid all of the nuts (Crawley and Long 1995; Steele and Smallwood 2001). DNA does not perfectly correct itself, allowing for mutations and consequent variation, while foxes do not eat all of the rabbits. Indeed, inefficiency and sub-optimality are both central to the functioning of any ecosystem (Abbott and Quink 1970; Forget 1992; Tomback 2001).

Sub-optimality arises in any situation involving multiple challenges. Farnsworth and Niklas (1995) point out that as the number of challenges increase upon a process, only solutions that are increasingly sub-optimal for each challenge will work. Thus, the idea that increased optimization at the level of the human organism will bring sustainability to the biosphere is wholly incorrect and dangerous.

Discussion

This paper set out to examine two premises. Firstly, that the circular economy is rooted in the same set of principles that underpin the natural world, and, secondly, that the principles underpinning the circular economy will increase the probability of a sustainable future. The Ellen MacArthur Foundation (EMF) clearly states that “The concept of the circular economy is grounded in the study of nonlinear systems, particularly living ones” (EMF 2012 p 22). However, this current paper clearly demonstrates that the natural world operates in a very different way from that portrayed in the circular economy literature. Table 1 sums up the findings, presenting the ‘natural’ principles adopted by circular economy thinkers (with references to where each principle is identified) and then contrasting this with the scientific research which clearly refutes the validity of these contrived principles.

The biosphere works very differently to any notion of a circular economy, primarily because of thermodynamic and system-related issues. In thermodynamic terms, the Earth is an open system and bears no similarity to any concept of spaceship Earth, closed loop nor circularity. Rather there is a massive flow of energy through the planet, and life works to convert free energy to waste energy, under the auspices of the second law of thermodynamics. Indeed, life is ultimately concerned with waste production. Increasing complexity requires increasing waste. Therefore, the concept of “zero waste” has no place in the natural world. More fundamentally, the concept of waste cannot be limited to considerations of materials and objects, but energy. The production of energetic waste lies at the base of ecosystem and economic functioning.

The idea stated by the EMF that biological components “are at least non-toxic and possibly even beneficial” (EMF 2012 p 22) lies at the heart of another significant error in much circular economic thinking (with exceptions such as the cradle-to-cradle approach) that technical and biological waste can be considered separately, the former requiring greater attention than the latter because of the differences in toxicity. Yet some of the greatest threats to the ecosystem services of our planet come from biological nutrients. Eutrophication threatens much of the biosphere and is the direct outcome of increased levels of biological nutrients, while climate destabilization is mostly attributable to biological nutrients, as is ocean acidification. Furthermore, biological nutrients are often non-renewable, since cycling relies on appropriate diversity and fluxes, which are damaged upon initial harvesting. The Newfoundland cod collapse did not recover despite fishing quotas, partly because the remaining, weakened populations became displaced by different species, which consequently altered the entire nutrient cycle (Hutchings and Reynolds 2004).

The return of nutrients to the biosphere will not necessarily precipitate recovery or restoration, a core objective of the circular economy. Furthermore, the concept of eco-effectiveness, set out by the EMF, claims that “The goal is not to minimize the cradle-to-grave flow of materials, but to generate cyclical, cradle-to-cradle ‘metabolisms’ that enable materials to maintain their status as resource” (EMF 2012, p 23). However, in the global market, few products are made, bought, disposed of and recycled in the same geographic location, and thus there is a vast export and import of nutrients associated with products across the globe. The problem here is that the biosphere consists of many local metabolic ecosystems, and if we do not return materials to the same geographic location from which we took them, then no form of localized metabolism can exist. Complete circles do not exist in manufacturing. Vast amounts of materials are farmed in one location and divested across the globe. Furthermore, the tempos of extraction and re-deposition rarely match, and there is no consideration of seasonal changes, so important in natural metabolic cycling.

In nature, cycling requires vast amounts of energy, yet considerations of cycling in the circular economy fail completely to account for the energetic waste production associated with such processes, particularly in terms of ‘renewable’ energy. A fixation with carbon also fails to take account of the broader ecological footprint of such processes (Skene 2010).

Having clarified that the self-proclaimed principles of the circular economy bear no resemblance to those that underpin the natural world, we must then consider if the circular economy could still be a useful human-generated

Table 1 Key principles of the circular economy discourse, and issues related to these, with relevant literature

Element	Issue
Recycling[1,2]	Renewable resources are actually less recyclable than non-renewable resources and pose a greater risk. Ecosystem services are central to the recycling of natural resources. Soil, forest, fisheries and coral reefs cannot be recycled. Recycling is energy-expensive[3,4]
Restoration[5,6,7,8,9]	As an emergent system, the biosphere is self-healing and cannot be reconstructed by humans. Reductionist, enlightenment thinking will not work[10,11,12,13]
Renewable energy use[6,9,14]	Most renewable technology (wind, photovoltaic, green fuel) is highly polluting in its manufacture and recycling or destroys habitats. Many approaches also use vast amounts of water (green fuels, nuclear)[15,16,17,18,19,20,21,39]
Elimination of waste[1,9]	Defeats waste-is-food concept if waste is reduced during production. It is thermodynamically impossible to grow economically while reducing waste. Energetic waste is as damaging as material waste. Nature operates as a waste pyramid, not as a perfect cube. Biological waste is as damaging as technical waste (e.g. eutrophication)[22,23]
Eliminating toxic chemicals[6]	Periodic table dictates that many toxic elements, either directly or in the process of mining and purifying, have unique physico-chemical properties that make them irreplaceable e.g. rare earth metals[4,24,25]
Eco-efficiency[7,9,26,27]	Nature is eco-inefficient. This is a consequence of systems theory, where each level is sub-optimal in order that the overall system functions. Optimality at the human level threatens all other levels[28,29]
Biological nutrient cycling[9]	Biological nutrients, at inappropriate concentrations and at the wrong times, are highly toxic to ecosystems (e.g. eutrophication and climate destabilization). There is a lack of awareness of this. They cannot just be poured back into nature[30,31]
Extended product life[2,14,26,32,33]	The long cycle is eschewed in the biosphere. Rapid turnover is key. Long-lived products cannot be easily replaced by greener new technology[34,35]
Economic growth[6,26,33]	Circles cannot deliver growth, only spirals can. Furthermore, increased service industry sector comes at a geographically separated cost to manufacturing[4,36,37,38]

[1] Shen and Qi (2012)
[2] Baily et al. (2013)
[3] Homer-Dixon et al. (1993)
[4] Skene and Murray (2015)
[5] Cooper (1999)
[6] EMF (2012)
[7] EU (2012)
[8] Nakajima (2000)
[9] UNEP (2006)
[10] Harrisson and Buchan (1934)
[11] Trosper (2005)
[12] Skene (2011)
[13] Cai et al. (2015)
[14] Preston (2012)
[15] Gardner (2007)
[16] Zhang et al. (2000)
[17] Farigone et al. (2008)
[18] Fitzherbert et al. (2008)
[19] Hurst (2010)
[20] Jessen et al. (2013)
[21] Li et al. (2013)
[22] Talbot (1920)
[23] Andersen (2007)
[24] Cohen (2007)
[25] Reller (2011)
[26] Schmidheiny (1992)
[27] Von Weizsäcker et al. (1997)
[28] Farnsworth and Niklas (1995)
[29] Tomback (2001)
[30] Reijnders (2008)
[31] Binzer et al. (2016)
[32] Boulding (1966)
[33] Stahel (1998)
[34] Vitousek and Sanford (1986)
[35] Vogt et al. (1986)
[36] Torras and Boyce (1998)
[37] Dietz et al. (2012)
[38] Fujii and Managi (2013)
[39] Dominguez-Faus et al. (2009)

concept in terms of delivering sustainability. Problems immediately arise here. Firstly, not only do the founding principles find no place in nature, but they actually work in the opposite direction. Take for example the concept of efficiency. Technological solutions tend towards efficiency, and target an optimized human condition. As this paper emphasizes, nature is sub-optimal at every level of organization, since complex systems require sub-optimality to function. If we accept that a sustainable future relies on the continuance of ecosystem services, then any move towards efficiency will threaten the very fabric of the biosphere.

Indeed, as Table 1 indicates, almost all of the principles underpinning the circular economy have the potential to destabilize the biosphere if they are applied in the real world. The consideration of biological nutrients as non-toxic is a dangerous error. The emphasis on renewable energy greatly threatens many ecosystems around the world. A proper ecological footprint, not solely reliant on carbon, needs to be calculated in order to assess how 'green' and renewable much of this energy is, while significant issues exist concerning water use in ethanol production, rare earth metals in wind turbines, a shortage of graphite and lithium for battery-powered vehicles and a shortage of uranium for nuclear reactors (Skene and Murray 2015).

Fundamentally, we must realize that the circular economy works against both the laws of thermodynamics and the underpinning principles of nature. Given this, it is highly unlikely that this concept will pave the way to a sustainable future.

Conclusions

We conclude by considering what a school of sustainability truly "grounded in the study of nonlinear systems, particularly living ones" (EMF 2012 p 22) would look like. Given that the biosphere has existed as a functioning entity for over three billion years, proving resilient across at least five mass extinction events and the snowball Earth of the Varangian glaciation, and that we have only been a part of this system for 0.001% of its existence (three million years compared to its three billion years), then it would seem sensible to view sustainability as an emergent biosphere property rather than a human construct. Our re-engagement with the biosphere requires us to embrace a number of its pivotal properties that have proved central to its longevity.

1. Sub-optimality: given that the biosphere is a system made up of a number of interacting levels of organization, each of these levels is expected to be sub-optimal and constrained by system-based asymptotes within which a sustainable system emerges. Optimization at the human level is therefore a strategy of doubtful value. Artificial intelligence (the branch of computer science concerned with making computers behave like humans) constrains computing systems to reinforce the failings of humans in terms of our detrimental impact on the planet. Artificial intelligence also tends towards the optimization of a process. Instead, we suggest that new technology should adopt ecological intelligence as its mentor, in terms of referencing sub-optimality rather than task-oriented optimization.
2. Pyramids, not cubes: nature is a waste-generating entity, and the cycling and re-energizing processes must be within natural limits. While recycling of biological nutrients is important, it must be at a rate and tempo that resonates with the natural world in order to avoid serious, toxic repercussions. Embodied energy relating to recycling must be included in any assessment of ecological footprints.
3. Bio-participation, not biomimicry, must be the overarching philosophy, where context is king. Bio-participation advocates the re-integration of humans within the biosphere system, representing strong sustainability, where participation rather than knowledge transfer ensures deeper symbiosis, as opposed to biomimicry, an example of weak sustainability, where natural processes, knowledge and designs are lifted into a new context for human use as substantive technology (Skene and Murray 2015). Transferring pieces of the biosphere into human activity and espousing this as a means to a sustainable future fails to grasp that the biosphere is an emergent system, not some tower made of little bricks. A reductionist approach will not resolve the issues facing us.

   We have the capacity to monitor impact on ecosystem functioning with technologies such as remote sensing and thus can evaluate the emergent consequences of our actions upon the planet. Remote sensing and other related Earth observation technologies offer a synoptic view of the Earth's surface, with records going back 30 years. These satellite sensors present new frontiers for biodiversity observations offering unprecedented global coverage at high spatial resolution with sophisticated measurements of the structure, composition, biochemical and biophysical properties of the Earth's ecosystems.

   It is a mistake to think that remote sensing technology is limited to monitoring net photosynthetic primary production. Satellite remote sensing can contribute significantly to four of the key areas in monitoring progress in sustainability: essential biodiversity variables, natural capital, biodiversity indicators and ecosystem services (Strand et al. 2007; Ayanu et al. 2012; Skidmore et al. 2015). Applications include species traits (leaf nitrogen, phosphorus and chlorophyll content, specific leaf area), species populations (occurrence, demography, disease prevalence), ecosystem structure (distribution, fragmentation, heterogeneity, land cover, vegetation height) and ecosystem function (productivity, vegetation phenology, inundation and fire occurrence), while measurement of atmospheric dust content acts as a proxy for erosion (Nagendra et al. 2013; LaRue et al. 2014; O'Connor et al. 2015; Pettorelli et al. 2016). Acoustic remote sensing sensors allow for production of detailed maps of bathymetry as well as the geological and biological components of the seabed, providing a wealth of information for mapping and analysing benthic habitats (Brown et al. 2011).

4. Appropriate asymptotes: as a system, each level of organization should operate within limits set by the overall system. This requires sensitive feedback. Again, technologies such as remote sensing can help here. Natural ceilings should be respected.
5. Real-time feedback: Nature is in constant communication with itself. Short cycles allow rapid change, and function predominates, rather than structure. Remote sensing offers the potential for appropriate feedback, allowing us to assess the impact of our actions at a system level. In an emergent system, you cannot predict what will happen, but you can measure it. It is essential to prioritize such ecological feedback as the central priority in terms of assessing the benefits or otherwise of our sustainability efforts.

The circular economy relies on tight loops, zero waste, extended lifetimes and a closed system, built on the Garden of Eden fantasy established by Boulding (1966) and reinforced in later work. But these observations of an imaginary garden are a fantasy and can never deliver sustainability. It is like believing in a flat Earth. No one can sail around a flat Earth. Ironically, circles can also never deliver growth. You need ever-increasing spirals for that. For economic growth requires maintenance respiration and growth respiration, and the more growth, the more expenditure is required to maintain the ever-expanding estate (Daly 1977). This is important and extremely concerning because it undermines the use of the circular economy concept as a means to a sustainable end, even in economic terms.

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