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Sustainability policy and practice: Is Nature an appropriate mentor?

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Abstract
Growing concern relating to the damage done to the Earth system by human activity has led to a proliferation of thinking in terms of ameliorating this impact. Many schools of thought, focused on economic, social and environmental sustainability, have adopted Nature as a mentor, claiming that by mimicking its forms, processes and ways of being, we can learn to live in such a way as to restore functionality to the planet while maintaining a vibrant economy. But how appropriate is it to consider Nature as a mentor? We examine three significant flaws in this approach: erroneous ecological knowledge, industry-ecology incompatibilities and the justification of Nature as a mentor. Given that most of these problems apply to almost all of the current schools of sustainability, we conclude by considering what threats to progress these flaws present, and how we can circumnavigate such difficulties.

Keywords Bio-participation · Emergence · Nonlinearity · Real-time feedback · Sub-optimality · Systems theory

1 Introduction

1.1 Origins

Growing concern relating to the impact of human activity on our planet has led to a proliferation of concepts centred around sustainability, mostly focusing upon human production systems, economics, energy supply, end-of-life fate and the use/misuse of resources. Almost all of these schools of thought view Nature as a mentor, providing inspiration as to how to live sustainably.

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1.2 The paradox in nature

Humans have had a difficult and fluctuating relationship with Nature. Indeed, the story of the human race has been defined by the changes in this relationship. From Nature we emerged and, as evidenced by the earliest human records, such as the cave paintings of the Upper Palaeolithic, we had a spiritual understanding, embracing Nature as a deity (Henneberg & Saniotis, 2009). Early gods were often part-animal, part-human, and the forces of Nature were eulogized as traits of these supreme beings.

From Thor to Gaia, the personality of Nature has been celebrated, ritualized and worshipped (Merchant, 2013). The idea of humans using Nature as a mentor and imitating it in early technology can be traced back to Plato, Aristotle and Democritus (Dicks & Blok, 2019), with biblical references to such mentorship such as “Consider the lilies of the field, how they grow: they neither toil nor spin” (Matthew 6:28) and “But ask the beasts, and they will teach you; the birds of the heavens, and they will tell you” (Job 12:7).

Yet the story of the human journey has also been one of distancing ourselves from our environment, reducing the relationship to utilization and abuse, rather than living within our natural boundaries. We have tamed the forces that previously held our population numbers in check, that dealt the cards of plenty and famine, of disease and resilience, of catastrophe and opportunity, the forces that shaped us, along with all of the other members of the Biosphere, for so long.

As we transitioned from hunter-gatherers to sedentary landowners with property rights, four significant changes occurred: the onset of agriculture, where surpluses could be generated, the onset of economics where surpluses could be traded, the onset of urbanization with specialized employment and the onset of inequality (Skene & Murray, 2017). Nature became increasingly viewed as a source and a sink rather than a deity. This position reached its climax during the industrial revolution, which still continues in many parts of the world today.

However, latterly, Nature has become a mentor for the green movement, with traits such as benevolence, circularity, self-control, eco-efficiency, zero waste, order, energy efficiency and optimization all becoming foundations of modern schools of thought such as closed-loop economics, natural capitalism, the circular economy, permaculture, sustainable product design, eco-design, biotecture, biomimicry and industrial ecology (Skene & Murray, 2017).

Yet in sharp contrast to these traits are the ideas of Nature raw in tooth and claw, competition and survival-of-the-fittest, as espoused in Darwinian evolutionary theory, and, more recently, the selfish gene, in Neo-Darwinism. A schism developed between ecological and evolutionary theory, with the former using an emergent, system-based model whilst the later employed a reductionist approach. This led to two very different interpretations of the character of Nature. The question then arises as to how Nature can apparently exhibit such contrasting personalities? What is the true nature of Nature? What is this mentor and what, if anything, can it teach us?

This paper seeks to examine how the living world actually works and then critically appraises the cultural appropriation of Nature in sustainability thinking. Three significant issues are identified in terms of current schools of thought on sustainability. We recognize that given that the Earth system is the only meaningful context in terms of our survival, then our solution space lies within the biosphere, not within human imaginings. The paper sets out what we can learn from Nature, what the consequences are for sustainability policy and practice, and what this means at the micro- and macro-scales.

Underpinning this is the recognition that if we are to build a future based on Nature as a mentor, then it is essential that the fundamental, underlying principles are anchored in meaningful and accurate ecology.

2 Materials and methods

An extensive examination of the major schools of sustainable thinking was undertaken in terms of claims made relating to how Nature functions. A number of recurring themes were identified. Each of these was scrutinized in the light of ecological and palaeoecological literature. Key characteristics of complex systems were identified in terms of how the Earth system functions. These were then used to explore issues within current sustainability thinking. Finally, an example of how to operationalize these characteristics in a practical way was presented, pointing towards key policy priorities moving forward.

3 A brief history of nature as a mentor

Nature is often portrayed as benevolent, wise, self-controlled, efficient, intelligent, frugal, charitable and ethically sound. This appreciation of Nature as a mentor is not a recent pursuit. Leonardo Da Vinci stated that "although human ingenuity may devise various inventions which, by the help of various instruments, answer to one and the same purpose, yet will it never discover any inventions more beautiful, more simple or more practical than those of Nature, because in her inventions there is nothing lacking and nothing superfluous" (da Vinci, 1906, p. 17).

Following the Whitby Synod in 664AD, western Christianity distanced itself from Nature as a mentor, fearing pantheism (the worship of Nature as an extension of God). This led to a departure from the eco-centric theology of Celtic Christianity, and the relinquishing of Nature as a mentor. The historian, Lynn White, went as far as to blame this schism for the ecological devastation that has since unfolded (White, 1967).

Yet the current economic model is not based on western Christianity, but rather on the principles of the Enlightenment, which eschews both church and state, calling for a free market economy. More salient to the present article, the Enlightenment also emphasized the rejection of Nature, which was viewed as a third obstacle to human progress in addition to church and state. The Enlightenment further separated man from Nature, with Condorcet, one of its chief architects, proclaiming "Nature hath fixed no limits on our hopes" (Condorcet, 1796, p. 120). Yet these so-called limits actually represent the essential feedback needed for true integration within the Earth system.

However, from the mid-nineteenth century, as smog-filled cities claimed an increasing toll upon human populations, thinkers, scientists and economists revisited the idea of Nature as a mentor. Roszak (1992, p. 14) reflects that: "the goal of ecopsychology is to bridge our culture's long-standing, historical gulf between the psychological and the ecological, to see the needs of the planet and the person as a continuum". It is only within this continuum that true sustainability, both social and environmental, can be located (Muhar et al. 2018; Okpara et al. 2018).

4 The characteristics of the earth system

4.1 Self-assembly and self-organization

Self-assembly and self-organization are two fundamental qualities of the Earth system. Each level of organization, from gene to biome, is composed of building blocks which self-assemble. At the beginning of life on Earth, molecules assembled without the intercession of a human chemist. Across evolutionary time, these molecular building blocks combined to produce cells, and over yet more time, groups of cells produced multi-cellular organisms. Organisms themselves became the building blocks of populations, which in turn were the building blocks of ecosystems.

Thus, the Earth system is the product of self-assembly across all of its levels of organization and is, itself, self-organized, or autopoietic (Varela et al., 1974), meaning that its functioning and architecture are not the properties of the building blocks, but of the overall system. Therefore, the Earth system emerges from an ever-expanding complexity of self-assembling building blocks, self-organizing into more complex building blocks. Arango-Rostrepo et al. (2019) demonstrate that the architecture and functionality of self-assembled structures is determined by the dissipation of matter and energy inherent in their formation.

Self-organization pervades all complex systems, whether they be microtubule assemblies, swimming bacteria or flocking birds (Desai & Mitchison, 1997; Gorshkov & Makar'eva, 2001; Papaseit et al., 2000). Bishop (2012, p. 6) noted that: "The interplay between parts and wholes in complex systems and their environments typically leads to the self-organization observed in such systems". At the other end of the scale, galaxies and planets are also self-organizing structures (Nozakura & Ikeuchi, 1984).

Ecological fragility can be understood as ecological simplification or the loss of complexity, wherein habitat destruction, severe disturbance or a lack of disturbance can lead to a decreased capacity to self-organize. In ecological succession, significant perturbation can lead to the collapse of the ecosystem, reorganizing from scratch, as described by Gunderson and Holling (2001) in their theory of panarchy. Here, ecosystems naturally revolve though four stages: growth, collapse, re-organization and rebirth.

Self-organization has significant implications for humanity, as part of the Earth system. We must understand that the Earth system will self-organize whether we acknowledge this or not, and thus we are subject to this process rather than drivers of it.

4.2 Nonlinearity

Nonlinearity is an extremely important systems characteristic, described as a situation where the changes of the output are not proportional to the changes of the input (Skene, 2019). One thing does not necessarily follow another and cause-and-effect breaks down because of unknowns in the system. Simple systems are predictable and follow linear paths (Wimsatt, 2007). A light switch can either lead to a light being on or off. A train will follow the same route between two destinations each time. Complex systems, such as the Earth system, fail to follow clear cause-and-effect and, instead, outcomes are often nonlinear, and, sometimes, dramatic.

These whole-system shifts are termed tipping points, where an apparently small change leads to dramatic transformation (Arnold, 1994; Milkoreit et al., 2018; Rocha et al., 2015). Strogatz (2003, p. 182) noted "every major unsolved problem in science—from consciousness to cancer to the collective craziness of the economy, is nonlinear". At its heart, nonlinearity points to an important issue: that the conceptualization of Nature as a machine, following the cause-and-effect approach of reductionism, is misplaced. Rather, Nature is a complex system, requiring a completely different understanding (Manzini, 1994).

4.3 Emergence

In complex systems, interactions of the parts give rise to properties that only belong to the whole (Bedau & Humphreys, 2008; Mill, 1843) and can be more or less than the whole (Morin, 2005). This is called emergence. Emergence is the opposite of reductionism, wherein something is built from simple building blocks. The selfish gene theory is a classic example of a reductionist concept, wherein the complexity of the biosphere is merely the extension of the genetic level of organization, as set out in *The Extended Phenotype* by Dawkins (1982).

Emergence delivers a dynamic unpredictability and is impossible to control. It resembles non-symbolic artificial intelligence on this level, wherein solutions emerge from the complexity of the global connectivity within the system, in contrast to symbolic artificial intelligence, which merely follows programmed algorithms in an 'if…then' manner (Skene, 2019). Resilience is an emergent property of complex systems. Hollnagel et al. (2006, p.16) note that "Resilience cannot be created—and it does not have to be, as it is already present as an inherent, emerging, property of all natural as well as engineered complex adaptive systems".

4.4 Real-time feedback

Connectivity is central to the functioning of any complex system. It represents the lifeblood of the system, permeating all and purveying information throughout. In order to tap into the benefits of being part of the Earth system, it is essential that we are plugged into it through perceiving and responding to the signals that pervade it. This signalling forms the basis of self-organization and of systemic control, particularly in terms of self-assembly and self-control (Jervis, 1997).

Regulation occurs through feedback; however, tipping points can also occur, representing nonlinearity (Dakos et al., 2019; Helms et al., 2009). This is important, as the concept of a Gaian homeostasis, fundamentally representing some form of planetary self-regulation, is questionable, given the underlying nonlinearity of complex systems. Thus, while feedback can lead to some form of control, it can also lead to systemic transformation, sometimes rapid, and the development of a completely new state. A further point worth noting is that feedback does impact on humanity even if we do not appear to be aware of it (Calvin & Bond-Lamberty, 2018; Thornton et al., 2017).

4.5 Sub-optimality

Given the emphasis on eco-efficiency and optimization in so much of the sustainability literature in terms of natural functioning, it can appear counter-intuitive to identify sub-optimality as a central feature of the Earth system and any other complex system. Yet this is a significant characteristic. When any given system is working well, then each individual component must operate at an appropriate level of sub-optimality (Farnsworth & Niklas, 1995). Trade-offs are the rule, not some inconvenience to be designed away. All living systems are “error-friendly”, or *Fehlerfreundlichkeit*, embracing the creative use of errors, error-production and error-tolerance (Von Weizsäuacker & Von Weizsäuacker, 1987). For any complex system to operate, every level must embrace sacrifice. We see this throughout Nature. The fox fails to catch all of the rabbits, the squirrel forgets where some of the nut stashes are hidden and the process of error repair allows some mutations to slip through, thus providing genetic variation (Abbott & Quink, 1970; Burgess, 2009; Crawley & Long, 1995; Forget, 1992; Steele & Smallwood, 2001; Tomback, 2001).

Indeed, the most prominent reason for the negative impact of modern humanity upon the Biosphere, and the existential threat to our species and many others, is our attempt at optimizing for ourselves (Skene, 2019). The pervading concept of survival of the fittest, from Spencer, has strengthened this concept, as has the path of progress towards some imagined humanitarian utopia. Only by being willing to embrace sub-optimality can we hope to repair the damage done. Yet the enlightenment and the age of technology promise increasing optimization for humanity, thus increasingly separating us from the essence of the Earth system.

5 Erroneous ecological foundations

There are many imagined characteristics attributed to the way in which Nature works that are fundamentally wrong, but keep appearing in sustainability literature. Here we consider a few of them.

5.1 Nature uses only the energy and resources that it needs

Perhaps one of the most glaring errors and misrepresentations of scientific knowledge is this claim. Here, the Biosphere is attributed with some benevolent ethical framework, pointing towards Nature as an appropriate mentor. Yet the situation couldn’t be further from the truth, and this misrepresentation has the potential to greatly exacerbate the destruction already occurring.

To understand the problem here, we need to examine the *Azolla* Event some 49 million years ago, long before humans were contributing to global destabilization (Speelman et al., 2009). *Azolla* is a freshwater fern. There was great surprise, therefore, when arctic coring experiments revealed an 18 m thick layer of *Azolla*, dating back to the Eocene, accompanied by a dramatic reduction in radiolarians, revealing a significant decline in salinity. At that time, the Arctic Ocean, then almost completely isolated from other oceans, is thought to have been composed of a dense saline lower layer and a freshwater upper layer enriched by nutrients from rivers. This nutrient enrichment led to a huge explosion in *Azolla* populations, which sank and drew down CO_2 and N, leading to a significant drop in atmospheric CO_2 levels (from 3500 to 650 ppm, current level 400 ppm). This drawdown of CO_2 in turn reduced arctic sea temperatures from 13 °C to −9 °C (due to a reverse greenhouse effect, where less heat leaving the planet was re-radiated back to the surface due to less CO_2), leading to the establishment of the Arctic ice cap (Backman et al., 2005; Brinkhuis et al., 2006).

The event was one of the first examples of positive feedback between nutrient enrichment and climate destabilization, currently viewed as a modern, human-made phenomenon. The cruel truth is that Nature does not use only the energy and resources it needs. Rather, Nature is an avaricious entity whose proliferation is only held in check by energy and resource shortages (von Liebig's Law of the Minimum).

For further proof, observe the outcome of eutrophication from human pollution, where increased nutrient availability quickly leads to ecosystems spinning out of control, as evidenced by toxic red tides and dead zones in the oceans in addition to widespread anoxia in our lakes and rivers (Brush, 2009). As predator and prey population sizes peak and trough, chasing each other through time, it is not management of its lust for food that reduces the predator population as prey become scarce, but, rather, starvation. There is no Gaian self-control apparent in eutrophied lakes with their dead fish and poisoned water. Nature does not use only the resources and energy it needs and neither does it display self-control when resources are available. This idea of checks and balances existing within the life forms on our planet is simply unjustified.

5.2 Nature always fits form to function, efficiently and elegantly

Here we see further development of the anthropomorphic personality of the 'mentor', adding elegance and efficiency to self-control. However, there is profligacy in Nature, seen clearly in sexual selection, where huge, unnecessary structures are developed particularly by male members of some species. These can lead to very inefficient functioning and even extinction.

Take, for example, the male Irish elk (*Megaloceros giganteus*), whose extinction is thought to have been aided by the spiralling enormity of its antlers, leading to a struggle to acquire sufficient nitrogen, calcium and phosphate for constructing them. This situation was exacerbated by the replacement of the willow-spruce communities of the Allerod interstadial by tundra vegetation in the Younger Dryas, which greatly reduced forage efficiency, leading to a physiological crisis (Moen et al., 1999). Such sexual selection is now not thought to benefit individuals anyhow, given that recent studies have shown that individuals lacking these "selective" benefits have similar sexual success (in terms of evolutionary fitness) as those with expensive appendages, or dominant behavioural patterns (Ercit & Gwynne, 2015; Rodríguez-Muñoz et al., 2010). Indeed, male guppies have been shown to trade sexual attractiveness for ejaculatory quality (Evans, 2010).

Ultimately, increased complexity requires increased conversion of free energy to waste, both in terms of development and maintenance respiration. Ecosystems undergo development (succession) by maximizing the rate of free energy transformation and entropic output, called the maximum power principle or maximum entropic production principle (Skene, 2013; Odum & Pinkerton, 1955; Schrödinger, 1944). Thus, Nature moves towards generating greater disorder in its surroundings in order to increase order within its ever more complicated whole (Fenchel, 1974).

Finally, resilience in ecosystems is an emergent property, born out of redundancy, wherein increasing numbers of forms carry out ecosystem functions, protecting function in situations of ecological simplification or localized extinction (Cowling et al., 1994). Thus, inefficient partitioning of forms between functions provides ecosystems with protection against attack. Nature is, fundamentally, profligate and inefficient in all that it does. The elegance of Nature is more difficult to judge.

5.3 Nature recycles and finds uses for everything

This representation of Nature as a responsible recycler does not match with the reality of food pyramids. If all waste is food, then why are there not food cubes (Skene, 2018)? The reality is that vast waste occurs in trophic pyramids, with only 10% of each level passing to the next level (Pauly & Christensen, 1995). It is the constant flow of free energy through the Biosphere, and its conversion to energetic waste that allows material waste to be 'reincarnated', not the act of cycling. There are also examples of ecosystems that recycle virtually nothing. For example, raised mires are 'raised' because nothing is recycled due to acidic, waterlogged conditions (Ingram, 1987).

Nature produces entropy (i.e. energy waste) very effectively. Energy requires constant replenishment because waste production is so extreme. Life, in many ways, is a waste generator. According to the second law of thermodynamics, in order to create complexity and stay far from thermodynamic equilibrium, waste must be produced. Nature is very wasteful. Toussaint and Schneider (1998, p. 3) have observed that: "As biosystems grow and develop, they should increase their total dissipation [waste production]". Lotka (1922, p. 149) concluded that "evolution…proceeds in such direction as to make total energy flux through the system a maximum compatible with the constraints". Furthermore, waste regeneration is an extremely energetically wasteful process in itself.

5.4 Nature is a closed system

Large amounts of energetic waste leave the planet continuously. It is only because equally large amounts of free energy arrive on the planet from the Sun that the whole system works. The Biosphere is not a closed system, but rather a gaping, open system, reliant on a river of energy flowing through it. During mass extinctions, often caused by comets and meteors impacting the planet, sulphate aerosols fill the atmosphere, reducing the flow of this energetic river and turning the Earth into a closed system briefly. The outcome is the collapse of biodiversity (Brugger et al., 2017; Kaiho & Oshima, 2017).

Nature is a profligate, wasteful operation that relies on vast amounts of energy continuously flowing through it to allow it to function. If we ran our human economy like this, we would need billions of tons of gold delivered to the planet from some extra-terrestrial benefactor every day just to break even.

Finally, ecosystems are dynamic systems, not static, and so disturbance is a significant part of the story (Kondoh, 2003). For example, many ecosystems require wide-scale fires on regular occasions, destroying the entire organization and resetting the process of succession (Hutto et al., 2015). While it may pay lip service to ecosystem functioning, it is unclear how biomimicry would embrace such a concept.

In reality, none of these characteristics are part of the curriculum vitae of Nature. Yet this fictional curriculum vitae is utilized to set out principles by which we are exhorted to learn from and base our sustainability theory upon, in schools such as closed-loop economics, natural capitalism, the circular economy, permaculture, sustainable product design, ecodesign, biotecture, biomimicry and industrial ecology.

6 Industry-ecology incompatibilities

6.1 Eco-industrial parks

Reference is often made to the Nordic eco-industrial parks such as Kalundborg in Denmark (examples of industrial symbiosis) as examples of zero waste economies based on the Earth system (e.g. Domenech & Davies, 2011; Ehrenfeld, 2000). However, this is a misrepresentation, common in several schools of economic sustainability thinking. These clusters are not closed loops. Energy and raw materials must continually flow through the site, while the whole purpose of the site is the sale of the products, which are exported all over the world. Thus, some of the waste generated in manufacturing may be recycled, but raw materials (whose extraction itself generates significant waste) must be imported and products must be exported from the site for the economy to function. Maintaining market share requires the conversion of currently owned products to waste, creating a vacuum that consumers fill by new purchases. Waste is essential for the maintenance of an appetite within the market. Products moving into waste around the world will be unlikely to find their way back to the eco-industrial parks from whence they emerged, and so these parks cannot be considered as closed loops. They are, by necessity, leaky colanders.

6.2 Significant differences between natural and human production

It is often emphasized that the infrastructure and processes by which products are produced likewise need to follow natural design (e.g. Benyus, 2002). This principle is also promulgated by the designers, William McDonough and Michael Braungart, who point out that the total biomass of ants on Earth is greater than the total biomass of humans, yet no “pollution” or ecological degradation results from their economic activities (McDonough & Braungart, 2002). They extol us to be more ant-like in our production methods.

However, this comparison is misjudged. Firstly, humans are warm-blooded, meaning that the energetic demands are much greater, per unit biomass, than that of ants, which are cold-blooded. Resting metabolic rates in ants have been calculated as 0.122 ml O_2 g^{-1} h^{-1} (Reinhold, 1999) while for humans a comparative figure is 0.210 ml O_2 g^{-1} h^{-1} (Martin & Palumbi, 1993), almost twice as high. More importantly, humans have huge extra-organismal energy costs and resource requirements, in terms of economics.

Globalized economic development involves massive expense and the population of humans is already reliant on vast amounts of material and energy from industrial output for its maintenance. We have artificially elevated the carrying capacity of the planet for our species well beyond natural limits, and economic development within the BRICS countries promises to require a further huge industrial effort to support, even if population remained constant (Skene & Murray, 2017). It is not just a question of how many of us there are, but the sum of our *per capita* consumption.

Smil (2001) estimated that at the end of the twentieth century, about 40% of the world’s population depended on fertilizer inputs to produce food, specifically, industrially produced ammonia from the Haber–Bosch process, an energy-expensive activity that contributes hugely to both eutrophication and climate destabilization. In 2005, approximately 100 Tg N from the Haber–Bosch process was used in global agriculture, whereas only 17 Tg N was consumed by humans in crop, dairy and meat products (UNEP, 2007). Thus, 83% of applied ammonia is wasted and much of this enters the Biosphere as a potent pollutant.

This brings us to an important point. While Nature does indeed operate in such a way as to generally avoid threatening its own survival (with the exception of significant events such as the Great Oxygenation Event, which wiped out most of the anoxic life forms then present), the scale of human production required to meet the needs of essential consumption (even before luxury consumption is considered) means that natural processes are wholly insufficient. Hickel (2017) calculated that in order to eradicate poverty, there would need to be a 175-fold increase in global GDP if we take earnings of $5/day as adequate. Thus, in order to eradicate poverty, we need to extract, produce and consume 175 times more materials than we presently do. Few of Nature's materials are made quickly enough or on a scale large enough to be of use to material engineers since natural processes usually operate at ambient temperatures and at near equilibrium conditions (Reed et al., 2009). Roy (1991) discusses the risks of over-interpreting tenuous connections between imitating Nature and creating startling new materials. More fundamentally, Nature cannot possibly act as a mentor for industrial production.

6.3 Sub-optimality and inefficiency are essential in nature

Foley claims that Nature entails 'optimizing' and that this is a model of sustainability since it is a 'closed-loop' system (Foley, 2010). This is incorrect on several levels. Firstly, Nature, as we have seen, is an open system, not a closed loop system. This serious error stems from the concept of spaceship Earth by Boulding (1966), which came to represent our planet as a closed system, allowing the idea of Nature as a self-sustaining, self-sufficient and self-controlled mentor to persist.

Secondly, any conceptualization of Nature as a mentor of efficiency and optimization for industrial processes and for product design also runs into problems. Volstad and Boks (2008) point out that evolution isn't a perfecting principle; it works on the principle of 'just good enough'. Thus, any concept of industrial efficiency and optimization should not be found in direct mimicking of Nature. Nature is sub-optimal at each level of organization, an essential quality in any emergent system. Human technology works in the opposite direction, seeking to optimize and increase efficiency.

Helms et al. (2009) have identified a number of problems with the misrepresentation of Nature in design, including weak problem definition, illegitimate pairing of biological solutions with design challenges, reductionist and context-free approaches, incomplete research and lack of feedback processes. Kaplinsky (2006) observes that human innovation is at its best when it goes beyond incrementalism.

This error is no more clearly seen than in an article by Knaus et al. (2016), where they claim that a particular biomimetic approach outperforms natural processes. Of course, this will be the case, in a reductionist experimental design, but sub-optimality is central to real-world processes that are context-based. The fixation with 'extended life' products, as set out by Stahel (1986), is another flawed approach. Nature fundamentally relies on fast turnover, not slow turnover, and any attempt to extend the lifetime of a product is likely to make it more difficult to recycle since that product must be designed to resist breakdown, and, thermodynamically, it will cost more energy over that lifetime to defy entropy.

6.4 Real-time continuous feedback in nature

Other differences between human design and natural design relate to timeframes. Natural systems are heavily reliant on real-time feedback from the Biosphere at many levels.

The Enlightenment has sought to free us from such feedback by insisting upon a reduction in the impact of environmental perturbation upon us (Condorcet, 1796). Yet perturbation is feedback. Without real-time continuous feedback, we cannot hope to achieve resonance with natural systems. An architect is unlikely to continue to adjust the design of a structure after it has been sold, while a product designer will have moved on to the next project, leaving static, non-dynamic structures and processes in place that are implacably isolated from essential feedback. Feedback within the Earth system is central to its self-assembling and self-organizing properties, while closely intertwined with the other key properties of the system, namely, nonlinearity, sub-optimality and emergence.

Humans tend to use information to optimize their own conditions and survival. This is not relevant within the Earth system. Take for example the idea of biosynergy, as represented by Flannery's (2017) kelp experiment. Flannery estimated that if we convert 10% of the ocean into kelp forest, the resultant benefits, in terms of green fuel, carbon dioxide drawdown and fish farming would be prodigious (fish for us to eat, a climate that preserves our existence and a fuel to continue to power our excessively energy-consuming lifestyles).

Yet there are considerable issues here. To begin with, well over 90% of the ocean is a desert in terms of biodiversity and productivity, because of low nutrient levels (Thompson, 1978), and this desert is expanding rapidly (Polovina et al., 2008). This leaves less than 10% available for kelp farming. To carry out the kelp experiment, we would need to fill all of the productive seas of the world with kelp, which would destroy the remaining coral reefs and make shipping very difficult.

Furthermore, kelp cannot grow at depths greater than 30 m, and only in cool waters between 5 and 20 degrees centigrade. But more fundamentally, there are ethical issues here. By engineering the planet further in order to combat the outcomes of our past engineering, we become masters of all, exceeding our place within the Earth system.

We cannot hope to re-integrate within the Earth system unless we become meaningful participants, not despots. It is not about mastering the bees (Matthews, 2019, quoting Maeterlink), but, rather, a much more fundamental respect for the sovereignty of Nature that is demanded here. The Ogiek people of Kenya, who have honey at the centre of their societal structure and function, have no word for 'beekeeper' in their language (Skene, 2019), because they view themselves as fellow sojourners with the bees, not as masters.

The subjective beauty and elegance of Nature appeals to many and invokes an almost spiritual admiration. Yet it is important to focus on the real science, in order to properly prepare for a sustainable future. The biosphere is an outcome of chemistry and physics, reliant on continuous free energy input and operating within the laws of thermodynamics. It is an open system and displays none of the moral character portrayed in much of the modern sustainability literature.

So, this profligate, greedy, avaricious, sub-optimal personality with no self-control whatsoever lies at the heart of our mentor. A bit like the human race really. Indeed, the huge human population explosion is a result of defying the limits placed on the natural world, much like *Azolla* in the Eocene. Humans make nutrients by mining and industrial production. Humans greedily feast on the planet's fragile resources. Humans use huge amounts of free energy. Temporarily freed from the constraints of limited resources, humans do exactly what Nature does in a similar situation: they proliferate and maximize entropy production. What then can be learnt from Nature?

This paper suggests that it will be more useful to focus on re-integrating into the Biosphere (Hofstra & Huisingh, 2014). Firstly, real-time feedback is essential. This is because, by attempting to re-integrate into an emergent system, humanity cannot rely on design to do this. It will be educated trial and error, but feedback is central.

It is feedback that maintains order within the biosphere, whose urges are tempered by system-level sub-optimality and inefficiency. Inefficiency lies at the heart of systems, wherein no single operator is optimized, but all levels share solution space and must sacrifice individualistic ambitions (Spash, 2016). The Earth system manages excessive entropic production through resetting.

The fixation on optimality and efficiency must also be revisited. By optimizing for the human level of organization, this places the larger system at risk, leading to collapse and rebuilding. Efficiency is not a property of Nature. Humanity must contribute to the appropriate level of intermediate disturbance that is found in the biosphere (Connell, 1975; Kratochwil, 2009). Appropriate indicators must be identified to measure system-level change. Remote sensing offers great possibilities here (Skene, 2018, 2019).

There is also a need to move away from carbon-dominated discussions. Clearly, greenhouse gases are a significant threat to our sustained existence on the planet. However, a wider focus is needed to ensure broader measures are in place, reflecting the overall health of the biosphere.

A carbon-based assessment of how ‘green’ our energy supply systems are will not be sufficient on its own. For example, how do energy transformation systems impact on water supplies? Ethanol production uses between two and eight million litres of water per MWh, whilst soybean diesel uses thirteen to twenty-seven million litres per MWh. This compares to petroleum extraction, which only uses 40 L of water per MWh (Dominguez-Faus et al., 2009).

Rare earth metals, essential in wind farms, are extremely toxic to extract (Li et al., 2013). Palm oil production devastates forest and uses large amounts of water while displacing agriculture (Wicke et al., 2011). Hence, it is essential to take a systems view, rather than focusing on a very limited set of issues and employing isolated thinking to each of these. Ecological footprints, rather than carbon footprints, must lead the way. Change should be system-based, not built on reductionist principles.

Thus, it is suggested that *bio-participation* offers the best hope of a sustainable future. Bio-participation is the re-integration of human activities within the Biosphere. Fundamental to this process is an awareness of our impact on the Earth system. Technology should focus primarily on providing this feedback.

Only with a radical transition involving worldview, institutions and technologies can maximum sustainable potential be achieved (Dusch et al., 2010). Marsden and Farioli (2015) emphasize a move towards an eco-economy, rather than a bio-economy.

Klaniecki et al. (2018) reveal that an individual’s behaviour is connected to the relationship they have with Nature. Most articles on biomimicry focus on one or two design aspects in Nature that can be incorporated into human technology, improving our quality of life while not impacting strongly upon the environment. Although Nature does indeed give us innovative solutions to problems that we face, such as Velcro and photosynthetic cells, we cannot rebuild the biosphere through lots of little mimics.

Sustainability theory and practice must move from viewing Nature as a machine to a place where we understand Nature as a system, much as science has shifted from Newtonian physics to the new physics during the twentieth century. Morin (1988, p. 77) writes that “the universe is no longer conceived according to the old Sovereign Principle of Order; it must be conceived in and through the links, the laws, the casual developments, that determine the interactions between the elements that form it, that is to say […], in the dialogic game between order/disorder/organization”.

7 Sustainability policies and practice

Key issues arise with many of the major sustainability policies and practices in terms of failing to acknowledge Earth system characteristics. Perhaps the most dominant global policy at present is the circular economy, based on a misguided perception of circularity in Nature (as can also be seen in closed-loop economics). However, as we have seen, the economy of Nature operates within an open system, not a closed system. Furthermore, Nature is eco-inefficient, not eco-efficient and generally operates using short cycles, not extended lifetimes (Skene, 2019).

Other sustainability policies, incorporating cleaner production, eco-design and the clean technology fund, focus almost completely on carbon issues. Whilst important, it is essential that all of the issues facing us, such as eutrophication, soil salinity, habitat destruction and fragmentation and species extinction, are also addressed, while not omitting social sustainability.

As an example, renewable energy (RE) technologies, whilst reducing carbon emissions, can significantly impact society and the environment in negative ways. Rare earth metals (REMs), so central to much of the RE sector as essential components in permanent magnets, cause significant damage to workers and children around the mines (Zhang et al., 2000). Enforced child labour in dangerous conditions represents a major issue in the supply of cobalt for the electric vehicle industry (ILO, 2017). A study by Jiao and Evans (2016) identified current electric vehicle practices as unsustainable from economic, social and environmental perspectives. Lithium mining in Chile and Bolivia impact negatively on the indigenous people there, while each 5 MW wind turbine generates 50 tonnes of non-recyclable plastic waste (Ziegler et al., 2018).

Yet current policies fail to address these issues, pushing ahead with an intensification of production of these technologies. These supply chain issues can be addressed (for example, permanent magnets containing REMs can be replaced by electromagnets, while the use of natural fibres in turbine blades can replace glass and carbon fibres) but would entail greater costs and greater inefficiency (ironically, a key Earth system characteristic). Yet our desire to optimize for ourselves, maximizing profits and ignoring the concept of trade-offs, undermines our efforts.

Other policy frameworks, such as natural capitalism, again rely on eco-efficiency, an anthropogenic concept not found in the Earth system, while zero-waste economics ignores the fact that life is, fundamentally, a dissipative process and that Nature is extremely wasteful (Skene, 2018).

A disastrous example of practice is the re-introduction of beavers in Scotland, backed by policy. Beavers are wonderful animals, but to re-introduce them without their predator, either the lynx or the bear, is a dangerous strategy, as the beaver populations will spiral out of control, consuming vast numbers of riparian trees and damaging the natural hydrological cycles, of which these trees play an essential part, as well impacting on carbon storage and habitat availability.

This reductionist approach, of re-introducing organisms without their predators, has occurred in Scotland before, with rabbits and then deer, both of which have severely damaged trees and impacted on soil stability. The Queensland cane toad is another disastrous example of this approach. The Earth system is complex, and you cannot just add a major herbivore without its prey.

8 A worked example of applying ecological intelligence to a sustainability challenge

Reforestation can occur in two ways: through natural regrowth following land abandonment (e.g. Foster, 1992) or by deliberate tree-planting programmes (e.g. Mather et al., 1999; Zhang et al., 2017). Regulatory policies relating to reforestation have been in place for over 150 years. Early legislation involved attempts at reducing flooding in France (1860), Switzerland (1876) and the USA (1911) (Shands, 1992; Rudel, 2019). More recently, reforestation programmes have focused on carbon sequestration.

Recent research casts serious doubt upon the use of artificially planted forests in terms of carbon sequestration. Yu et al. (2019) have shown that natural forests are better at carbon sequestration, and use less water, than planted forests. Meanwhile, an important study by Friggens et al. (2020) has demonstrated that planting trees in rich organic soils can actually lead to a net carbon release on a decadal timescale (40 years), due to changes in microbial and fungal activity in the soil. Soil organic carbon is released at a greater rate than can be sequestered by the tree. This is a classic example of the need to assess ecosystem carbon relations, rather than approaching the issue with a reductionist "plant a tree, suck up carbon" philosophy. Planting trees in non-forest soils is not the answer.

This paper points to a different approach. Firstly, the Earth system is recognized as a complex system that has been functioning successfully for 3.7 billion years without our interference. This means the solution is most likely to have been figured out already.

Secondly, a forest does not equate to trees in a field. Ecological succession takes many years, and the forest soil represents the forest as much as the trees do. Succession is the result of thousands of species interacting over 150 years, subtly altering the soil and eventually producing a forest soil. Shrubs, herbs, trees, bacteria, fungi and animals are all involved (Hiremath & Ewel, 2001).

Thirdly, fewer than 1% of the micro-organisms in soil can be cultivated and studied (Amann et al., 1995), meaning that we have no idea how to recreate these processes. Finally, natural forests will have multiple ecological functions (Kučera et al., 2020), far beyond carbon sequestration, and there will be essential trade-offs requiring sub-optimization, as demonstrated earlier. Optimizing for carbon sequestration would run counter to all that we understand about complex systems.

For all of these reasons, this paper would suggest the following approach: land should be left, free from interference, allowing ecological succession to produce a natural forest, rich in diversity, with appropriate soil, understory and canopy layers, providing a resilient ecology that will successfully provide services to ourselves and the other organisms. This approach embraces the key characteristics of the Earth system discussed earlier. It will take longer, but the results will be the most fitting and designed and executed by the Earth system itself. This true mentoring, where we learn to live within the Earth system, rather than to control and design our way out of the problems that we have created, is key to this issue and to all of the other challenges. Ecological intelligence far outstrips human intelligence in every situation (Skene, 2019).

9 Conclusions

Grasping the meaning of Nature requires integration within Nature (Basu et al., 2020; Ives et al., 2018; Klaniecki et al., 2018). A recognition of the core characteristics of the Earth system must lie at the heart of policy and practice. Nature cannot inform us on economics, efficient production, optimization, conservation, zero-waste strategies, efficient energy use nor self-control. None of these traits are found in the natural world. However, Nature is the perfect mentor for sustainable living, the importance of real-time continuous feedback, the role of sub-optimality at any given level, resilience, recovery, emergence, our re-integration into the Biosphere and our understanding of our place in the grand scheme. So, let's listen to Nature, and reference the true lessons that are there for the learning. The mentor awaits us, but finds us conversing with the mirror in the corner rather than entering into a meaningful conversation.

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