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Viewpoint

Bioengineering the biosphere?

Ricard Solé [a,b,c,*]

[a] ICREA-Complex Systems Lab, Universitat Pompeu Fabra – PRBB, Dr. Aiguader 88, 08003 Barcelona, Spain
[b] Institut de Biologia Evolutiva, UPF-CSIC, Barcelona, Spain
[c] Santa Fe Institute, 1399 Hyde Park Road, NM 87501, USA

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ABSTRACT

Our planet is experiencing an accelerated process of change associated to a variety of anthropogenic phenomena. The future of this transformation is uncertain, but there is general agreement about its negative unfolding that might threaten our own survival. Furthermore, the pace of the expected changes is likely to be abrupt: catastrophic shifts might be the most likely outcome of this ongoing, apparently slow process. Although different strategies for geo-engineering the planet have been advanced, none seem likely to safely revert the large-scale problems associated to carbon dioxide accumulation or ecosystem degradation. An alternative possibility considered here is inspired in the rapidly growing potential for engineering living systems. It would involve designing synthetic organisms capable of reproducing and expanding to large geographic scales with the goal of achieving a long-term or a transient restoration of ecosystem-level homeostasis. Such a regional or even planetary-scale engineering would have to deal with the complexity of our biosphere. It will require not only a proper design of organisms but also understanding their place within ecological networks and their evolvability. This is a likely future scenario that will require integration of ideas coming from currently weakly connected domains, including synthetic biology, ecological and genome engineering, evolutionary theory, climate science, biogeography and invasion ecology, among others.

1. Introduction

In a few human generations, our planet is likely to experience large-scale changes that will jeopardise the stability of our complex social and economic structures. Energy and demographic crises, biodiversity declines, increasingly frequent extreme events, along with water shortage and crop failure associated to climate change are already sending us warning signals (Scheffer et al., 2001; Scheffer and Carpenter, 2003; Scheffer, 2009; Dawson et al., 2011; Lenton, 2011a; Barnovsky et al., 2012). We live in a time where the knowledge of our planet is greater than ever and the potential threads seem rather well defined. Scientists have depicted a grim perspective of our future. We are a major transforming force that is rapidly pushing our planet towards new, undesirable states. A consensus has emerged from climate science about a future, hotter planet that will make life difficult, if not simply incompatible, with a sustainable society (Lenton et al., 2008). We have enjoyed a favourable window of 10,000 years, the so called Holocene period, where humans have been able to flourish as a dominant, creative and rapidly expanding species but also as a global geological force. The new human-driven era that emerges from the Industrial Revolution, the so called Anthropocene, is dominated by an increasingly obvious impact of human activities that are pushing the Earth outside its regulatory capacity (Steffen et al., 2011).

As it occurs with many other complex systems (May, 1977) continuous changes in parameters that control the state of given system often end up in catastrophic shifts once tipping points are reached (Scheffer, 2009; Solé, 2011; Hughes et al., 2013). This is the case of the average concentration of carbon dioxide: once some critical levels are reached, our current climate state is likely to be replaced by another global pattern resulting from a runaway greenhouse effect (Solomon et al., 2007; New et al., 2011). A macroecological analysis of energy use and economic activity also indicates that the current tendency might end in a social and economic collapse (Rockstrom et al., 2009). Similarly, many ecological systems will face rapid declines towards degraded and even bare systems with no species left (Suding et al., 2004). This is illustrated by arid and semiarid ecosystems (Rietkerk and

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[*] Correspondence to: ICREA-Complex Systems Lab, Universitat Pompeu Fabra – PRBB, Dr. Aiguader 88, 08003 Barcelona, Spain.
Tel.: +34 933160530; fax: +34 933160540.

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van de Koppel, 1997; Scanlon et al., 2007; Kéfi et al., 2007; Solé, 2007) where warming, steady declines in rainfall and increased grazing will trigger rapid changes towards a desert state and are specially vulnerable (Thornton et al., 2011). Evidence for such sudden changes exist, as shown by the shift from a green Sahara to the current desert state, which took place 5500 years ago (Foley et al., 2003). Rainforest ecosystems, reefs and boreal forests might also face serious declines (Barnovsky et al., 2012; Hughes et al., 2013). In some cases, as illustrated by the collapse of fisheries, they have already occurred while the awareness and reactivity of society to such sudden loss has been far from optimal (Scheffer et al., 2003).

Many studies have addressed possible ways for remediating these potentially catastrophic situations. Humans too have been effectively operating as ecosystem engineers (Vitousek et al., 1997) by adapting the biosphere to their needs, while expanding their populations in a hyper exponential fashion. Because our long-term influence, vast amounts of energy-intensive fossil fuels have been used to power our civilisation, reinforced by the accelerated growth of agriculture from the Neolithic revolution. Profound alterations of the water and nitrogen cycles are a direct consequence of these unsustainable practices. Moreover, an ongoing rearrangement of biotic systems has been taking place, mainly due to habitat loss and biological invasions (Elton, 1958; Drake et al., 1989). By doing that, we are changing the face of our biosphere, placing ourselves close to a planetary-level critical transition. Can the situation be reverted?

Existing approaches, to be summarised below, include reforestation, geo-engineering and emission cuts, among others. However, the scale of the problem, the staggering economic costs and its accelerating pace constitute a major barrier to restore previous states in a sustainable way (Folke et al., 2011). Moreover, we need to face the nature of our biosphere as a complex adaptive system with multiple interacting species, nonlinear responses, complex feedbacks and self-organizing patterns (Levin, 2002; Solé and Levin, 2002). There is a strong asymmetry between cumulative anthropogenic impacts and our slow and limited capacity for counterbalancing them on time. Such asymmetry implies that we might have a narrow time window to properly react to the challenge. In this paper I suggest a rather different approach, which requires an engineering perspective, grounded in the design of modified life forms and intervention. But, above all, requires a new merging of disciplines, particularly at the unexplored boundaries between synthetic biology and ecological theory. Because it requires humans as agents for Earths transformation, the remediation strategies suggested here imply a modification of natural ecosystems. This is, no doubt, a controversial matter (Callaway, 2013). The advantages and drawbacks of this approach, along with implementation strategies, are outlined below.

2. Terraforming Earth?

Restoring a sustainable Earths state necessarily requires to confront the scales of space, time and energy on the planetary level. That means that whatever the solutions found, they go beyond any human standard engineering scale. Before looking at our own biosphere, let us first make a turn by considering the other single scenario where such engineering problem has been proposed, namely the problem of "Terraforming" Mars (McKay et al., 1991). The idea is, in a nutshell, to introduce artificial modifications that trigger a runaway process capable of displacing the planet's state towards a new steady state with higher temperatures, water levels and thicker atmosphere. That could be achieved through the use of greenhouse gases (Lovelock, 1988) although at very high costs. It would be also achievable or by means of appropriate microorganisms (Rothschild and Mancinelli, 2001) capable of adapting and growing under extreme conditions. In both cases, a relatively small perturbation is expected to get amplified, ultimately affecting the planets geochemical cycles. The first possibility is unlikely to be feasible due to the associated costs. But the use of extremophiles, such as some bacterial species of *Carnobacterium* (Rothschild and Mancinelli, 2001; Nicholson et al., 2012; Keith, 2000) have been shown to tolerate extreme conditions (including low pressures and temperatures along with anoxia).

In this paper we will use the previous scenario as a starting point to discuss how the release of genetically manipulated organisms could be used to restore habitat and climate unbalances at local, regional and even global scales. Such possibility has not been raised before. Instead, within the context of global warming, existing proposals consider geoengineering (Lovelock and Rapley, 2007; Schneider, 2008; Vaughan and Lenton, 2011; Caldeira et al., 2013). In contrast with reduction of emissions, this climate engineering scheme (directed to mitigate global warming) operates directly on diverse physical or chemical factors. The cost of most proposed solutions is typically enormous, as a consequence of the massive scales involved. These solutions include a broad variety of possibilities, from hundreds of thousands of towers to capture carbon dioxide to trillions of small, free-flying spacecrafts (Vaughan and Lenton, 2011; Caldeira et al., 2013). Lower costs but high risks are expected from using aerosols, to be injected in the stratosphere to counterbalance greenhouse gases (Lovelock, 2008). Other strategies, such as iron seeding to trigger plankton blooms have failed to meet their expectations. Even despite the limitations of these proposals, a common message is that the price of not preparing for the future will be much higher than the investment in any of the previous possibilities (Schneider and Mesirow, 1976).

How to deal with the large scale problem that we face here? If geoengineering is not the right approach, what can be the alternative? We should look for feasible solutions capable of (a) solving the scale problem at a reasonable cost, (b) restoring the desired systems state over an appropriate time scale and (c) minimize the risks of undesired evolutionary dynamics. The approach suggested here is that such solutions might soon exist at the crossroads between ecosystem engineering (Odum and Odum, 2003) and different approaches oriented towards engineering living systems, particularly synthetic biology (Drubin et al., 2007) and genetic engineering of plants (Mittler and Blumwald, 2010). So far, all these approaches have been developed within a lab or farm context where containment is a major concern (Church, 2005; Dana et al., 2012). Not surprisingly, biosafety issues related to the potential release of engineered organisms or genetic material have become part of the research agenda. Given all the unknowns, containment has been at the centre of these disciplines as much as their design principles. What I want to suggest is an orthogonal, but may be complementary: Terraforming Earth by engineering new synthetic organisms capable of counterbalancing undesirable trends. A major difference of this type of engineering is obvious and crucially departs from geoengineering: since living entities self-replicate, an engineered organism capable of large-scale dispersal would eventually reach, by growth and reproduction, the desired scale. This could be achieved within reasonably short time scales and the proposal is not limited to capturing carbon dioxide: as an example, engineered bacteria could be designed to help plants facing stressful habitat conditions in order to improve their survival, perhaps enhancing desirable soil microbial communities. Other manipulations affecting photosynthetic efficiency or light-sensing properties could also change the ways we can repair damaged habitats (see below).

The release of a living system that has to spread over large biogeographic areas should be considered cautiously (Snow et al., 2005; Pilson and Prendeville, 2004). How they can affect