The role of closed ecological systems in carbon cycle modelling

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Abstract

Acquiring a mechanistic understanding of the role of the biotic feedbacks on the links between atmospheric CO_2 concentrations and temperature is essential for trustworthy climate predictions. Currently, computer based simulations are the only available tool to estimate the global impact of the biotic feedbacks on future atmospheric CO_2 and temperatures. Here we propose an alternative and complementary approaches by using materially closed and energetically open analogue/physical models of the carbon cycle. We argue that there is potential in using a materially closed approach to improve our understanding of the magnitude and sign of many biotic feedbacks, and that recent technological advance make this feasible. We also suggest how such systems could be designed and discuss the advantages and limitations of establishing physical models of the global carbon cycle.

1 Background

As a species we are effectively "trapped" on a planet which, for all practical purposes, is materially closed, but energetically open (Fuller and Snyder 1969). With the exception of the cosmic debris that falls into the atmosphere and the negligible quantities of matter in satellites and light gases that escape into outer space, the Earth is materially closed. We have no real choice other than to survive within this closed system and, more critically, to ensure that it remains sustainable. From cells to ecosystems and through to biomes, there is no other biological or ecological scale besides the Biosphere (Vernadsky 1926) at which life is able to persist in the absence of significant matter exchange; the consequences for ecological systems at scales below the planetary scale are enormous (see section 2).

To date, our inherent inability to replicate the Earth as an experimental system has considerably hindered our understanding of how the Earth functions. Indeed, the consequences of increasing atmospheric concentrations of greenhouse gas emissions, arguably the most challenging environmental issue of today, are extremely difficult to predict (Solomon et al. 2007). The urgent need for trustworthy predictions of the future climate, together with an improved understanding of the way in which the Earth functions, has fuelled the rapid development of computer-based climate-carbon cycle coupled models, also known as Earth System Models (ESM) (Lenton 2000, Friedlingstein et al. 2006). However, there are concerns associated with embedded parameterisation and conflicting model outputs (Friedlingstein et al. 2006). The ESM results presented in the latest IPCC report (Solomon et al. 2007) indicated large uncertainties in predicting even the relatively short term temperature increase by the end of the century. With the future climate of the Earth becoming a major concern to governments, policymakers and citizens alike throughout the world (Solomon, et al. 2007), we need all the available tools to help predict and mitigate future climate related threats. However, somewhat worryingly, ESM are currently the only available tool to make future predictions.

In most areas of science and technology, at some point, use has been made of analogue (physical) models to force progress (Frigg 2006). For example, the wind tunnel was and still is an essential tool in aeronautical and structural design despite extremely complex and well-tested digital models of air flow. When dealing with complex systems, an analogue is frequently constructed at an early stage. We believe that in the scientific dash to provide climate change predictions this initial step of potential importance has been omitted. An analogue approach could provide an alternative and independent tool capable of assessing the impacts of future CO_2 concentrations and temperatures on biotic C feedback. Established in materially closed but energetically open systems (just as the Earth), we argue that such physical/analogue models of the C cycle are well suited to model biotic C feedbacks. This is due to two essential features: i) ability to continuously and simultaneously allow two-way feedbacks between the biotic and abiotic components to take place and ii) ability to provide detailed mass balance. Moreover, studying the characteristics and behaviour of systems which have been physically isolated from the surrounding space has proved to be a fundamental step in many fields of research; physics (in thermodynamics) and chemistry (Miller and Urey 1959, testing for the occurrence of chemical evolution) being the most obvious examples. Thus, we contend that using CES as analogue model systems for climate change research holds promise of answering some fundamental questions about the functioning of ecosystems and, more specifically, about the carbon (C) cycle which underpins them. In ecology, CES represent the only materially closed systems we have available for study below the scale of the whole planet! But do we actually have the ecological, biological and technological expertise to establish to establish CESs as model systems for climate change research?

2 Lessons from the past

It could be argued that the history of CES started with Joseph Priestley's experiments with mice, candles and the green alga, Chlorella (Priestley 1775) - which eventually led to the discovery of oxygen. Much more recently, CES have been primarily used in attempts to establish bioregenerative life support systems to supply and regenerate the air, food, water and recycling waste required for human survival in space such as Bios 3 (Salisbury, et al. 1997) and Laboratory Biosphere (Nelson et al. 2003a) and, secondarily, as a basic tool in aquatic ecology (Taub 1974, Taub 2009). However, our understanding of what makes a closed system self sustainable is still poor. Winogradsky's columns (Winogradsky 1887) or

Folsome's (Folsome and Hanson 1986) small and rather simple aquatic systems (airtight vials containing algae and microorganisms) stayed 'alive' more than 30 years, whilst the largest and most sophisticated attempt to create an Earth analogue - Biosphere 2 project (Nelson et al. 1993) reached dangerous levels of O_2 and CO_2 in less than a year (Cohen and Tilman 1996). This suggests a lack of mechanistic understanding of the basic principles that govern the behaviour of CES.

The most often outcome of longer term closure is a collapse of the ecological system due to imbalances in the autotrophic and heterotrophic gas fluxes (O_2 vs. CO_2) and/or the nutrient release and uptake cycles (waste decomposition vs. nutrient absorption) (Nelson et al. 2003b, Nita 2003). The Biosphere 2 project drew attention to the fact that species diversity alone is not sufficient to induce a homeostatic and self-regulating (which implies that the system remains within bounds of environmental variables compatible with life) Gaian effect (Lovelock and Margulis 1974; Wilkinson 2003). It did signal, however, that if the amounts of elements (e.g. carbon and nitrogen) in the main pools (atmosphere, biomass, soil and ocean) and the mass ratios between the pools are departing from those of the Earth, there might be severe consequences for the homeostatic capability of the system; the extensive use of highly fertile soil (high in C and N) in the setup of Biosphere 2 led to the accumulation of dangerous levels of CO_2 and N_2O in the atmosphere accompanied by a drastic decrease in atmospheric O_2 (Cohen and Tilman 1996).

In the attempts to use CES as bioregenerative life support systems for space exploration it became increasingly evident that some of the challenges facing the these systems - such as renewal of water and atmosphere, nutrient cycling and waste recycling - are strikingly similar to those of maintaining a sustainable global biosphere (Nelson, et al. 2003b). Notably, CES proved to be ideal for mass balance studies, but also for detecting subtle effects and feedbacks, largely because of the amplification effect via accumulation over time and which would otherwise be beyond the resolution of our materially open experimental approaches (Nelson, et al. 2003b, Dempster 2008). For example this feature has made CES the right tool for detecting unwanted trace compound accumulations with potential major effects on the stability of the systems (e.g. damaging accumulation of Na^+ in the soil or ethylene in the air; Wheeler et al. 1996). Such subtle effects could not be detected in materially open systems (Dempster 2008).

Early days of CES found that achieving a hermetic sealing is a non-trivial technical challenge (Wheeler et al 1991, Corey and Wheeler 1992, Dempster 2008) for the establishment of reliable CES. Meanwhile, the introduction of gas tracers (N_2O and helium) and less gas permeable materials allowed to reduce the contamination rates in the more recent attempts to create CES (Kliss et al. 2003 Lukac et al. 2010). This should permit the establishment of smaller scale but replicated CES (Lukac et al .2010), previously avoided due to the larger surface per volume ratio where minute phisical leaks or permeation through the wals could lead to very high atmospheric contamination rates.

3 CESs as physical models for global carbon cycle modelling

Currently we have reliable estimates of the global carbon (C) pools (Albritton, et al. 2001), which allows for establishment of closed systems with precisely the same ratios of C in the main pools as on Earth. Recent work showed that by combining the technological know-how gained through the construction of life-support CES with the estimates of the global C pools and fluxes, it is technologically feasible to set up small-scale materially closed systems as analogue models for C modelling which allow a continuous and detailed monitoring of the relevant environmental parameters (Lukac *et al.* 2010). Such systems do not have to be indefinitely self-sustainable, but need to realistically emulate the global C polls and fluxes for the duration of the experimental runs.

A simple terrestrial only analogue model of the pre-industrial C cycle with total volume of ~120L could represent (*pro rata*) the 2011 GtC in soil, 900 GtC in vegetation and 560 GtC in the pre-industrial atmosphere by adding e.g. 2.85 g of dry arable soil (2.13% C), 0.53 g with 0.528 g FW (14% DW) plant biomass and adjusting the atmospheric CO_2 at 280 ppm. Light intensity can then be adjusted in order to balance the CO_2 uptake and release and maintain the atmospheric CO_2 concentration ~ 280ppm, thus simulating the preindustrial atmospheric CO_2 concentrations. Using the aforementioned (*pro rata*) representation of the terrestrial C pools and the setup of Lukac et al. (2010) we found that, the atmospheric CO_2 concentration tends to stabilise (i.e. weekly slope of CO_2 concentration was not different from zero) near the preindustrial atmospheric CO_2 concentrations a couple of weeks from the onset (Fig. 1). Moreover, the presence or absence of light resulted in average daily CO_2 oscillations of ~ 9 p.p.m.v., of similar magnitude to the seasonal oscillations observed in the Keeling curve (up to ~7 p.p.m.v.) and driven by the terrestrial biosphere (Keeling and Shertz 1992).

Such systems can thus be designed to address a multitude of key questions that have never been tackled except in computer simulations. For example, a less explored angle of CES is their use for detecting biotic feedbacks, which have became pivotal in understanding the relationship between the CO_2 concentration in the atmosphere and global temperature change (Cox, et al. 2000). Recently, the ESMs started to include biological feedbacks, however, the magnitude of the modelled responses, and even their sign, are highly dependent on the sensitivity of plant growth and soil respiration to temperature, which in turn are often the output from another digital model (Jones, et al. 2003). In climate-carbon cycle coupled

ESM models the strength of the C cycle feedbacks is summarised as the relative gain (g) in atmospheric CO_2 concentrations in relation to the uncoupled runs and depends on three parameters: i) β, the sensitivity of land and ocean carbon uptake to CO_2 (GtC/p.p.m.v. CO_2), ii) γ, the sensitivity of land and ocean carbon uptake to temperature (Gt C/ºC) and iii) α, the GCM temperature sensitivity to CO_2 (Friedlinstein et al. 2003, 2006). Designed with good temperature control capabilities and a dynamic system of temperature control depending on the CO_2 concentrations according to different climate sensitivities (i.e. mimicking the α) such systems could focus on estimating the global biotic responses (β and γ). Any observed changes in C pools will thus not be a result of the very simplistic temperature dependence equations (Q10 values; Davidson et al. 2006), but of real biological processes driven by the continuous two-way feedback between biotic (plant and rhizosphere) and abiotic components (atmosphere and soil). Currently, global biotic C responses to climate change are mainly parameterised on the basis of data originating from warming and Free-Air CO_2 Enrichment (FACE) experiments. However, these approaches do not fully incorporate the continuous two-way feedbacks between the biotic and abiotic components. The feedback loop can be closed both in computer and in analogue models, however we argue that not having to digitally reconstruct and parameterize all feedbacks is a major advantage of materially closed analogue models.

The still arguable role of nitrogen availability and deposition in the terrestrial biosphere's potential to slow the global atmospheric CO_2 build up (Reich, et al. 2006) could also be tested for the first time outside a digital model. Another intriguing opportunity here, is largely facilitated by the fact that, in *pro rata* systems, the daily C (as p.p.m.v CO_2) uptake and release during the daytime and night time in stabilised and C neutral systems (as those presented in Fig. 1d) is similar to the estimated annual terrestrial C uptake. This information can be used as proxy for devising multiple IPCC CO_2 emissions scenarios which could be simulated over a shorter period of time. By simultaneously running scenarios with control (no emissions) and emissions and without physically forcing a climate sensitivity (α), the difference between the reached atmospheric CO_2 concentrations would allow to quantify the gain due to biotic C feedbacks (g).

4 Challenges and limitations

Several challenges still have to be overcome if we are to use CES as reliable model systems for climate change research. Leaving aside the cost factor, we argue that the system size or the biological diversity included in the systems (considering Folsome's 1-5L flasks and over 4000 species of plants and animals in Biosphere 2) have already proved not to be the most critical aspects. The lack of replication and/or unrealistic amounts and mass ratios of the main C and N pools proved to be the major drawback for the Biosphere 2 project and this alone makes a strong argument for smaller but replicated systems. One possible limitation of this approach is that certain processes observed in smaller scale systems might show different sensitivities relative to the larger ones. The existence and eventual strength of such a relationship, however, remain unexplored. At present this issue also affects the ESMs and could be tackled by setting up analogue models of different sizes to verify if the observed processes scale up linearly with size. In addition, the choice of species and the artificial nature of the assembled communities could potentially affect the functioning of the analogue models, a criticism which has often put forward to explain the failure of the Biosphere 2 to sustain the ecosystem services within the boundaries of human habitation (Cohen and Tilman 1996). We acknowledge that the construction of analogue models that incorporate elements of global biotic and climatic heterogeneity represents a major challenge, but we argue that this is achievable.

Evidently, some aspects of the carbon cycle cannot be captured in analogue models. It has been a challenge so far to design systems which permit realistic transfer of matter between separated sub-systems (e.g. between the terrestrial and aquatic components) short-term C cycle (which includes photosynthesis, respiration, atmosphere–ocean exchange of CO_2). The long-term C cycle (Berner 1993) and the associated processes that occur over millions of years such as the C exchange between the bedrock and the surficial system or aspects of the biogeochemical cycles which are closely tied to physics, especially in the ocean (high pressure or depth), can only be addressed by digital models. Further, at the present there is little information whether including both terrestrial and aquatic components leads to an increase or has no effect on the homeostatic capability and viability of such systems in the long-term. Over geological timescales, the concentration of atmospheric CO_2 is regulated by biogeochemical processes such as carbonate and silicate weathering (Walker, et al. 1981) where the oceans ultimately play an important role. However, over ecological timescales, which happens to be the scale at which our anthropogenic impact is manifested, the level of atmospheric CO_2 is predominantly controlled by biological C uptake and release via photosynthesis and respiration (e.g. seasonal variation in the Mauna Loa curve; Keeling 1976). In this respect, a physical model without an aquatic compartment should still be informative depending on the addressed question.

5 Conclusions

Currently, we can only speculate what would happen in a CES setup as physical model for biotic C feedbacks (as described in section 3) if we increase the temperature or if we simulate the greenhouse effect by controlling the temperature depending on the atmospheric CO_2 concentration under different climate sensitivity scenarios. We deem CES as crucial in their role as analogue models for climate change research, since they offer the possibility of studying some of the mechanisms and process that otherwise would be almost impossible to detect in materially open systems or could be masked at the global scale. Although still ridden with challenges, the use of CES as physical (analogue) models for climate change research is the only available approach to sit alongside, validate and challenge the increasingly complex digital models. Whilst the development of analogue modelling for climate change research is still at an early stage, we argue that this approach has the potential to uncover key properties of the processes that drive global biotic feedbacks which will ultimately help to predict future Earth system changes using ESMs with greater certainty.

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Figure legend

Average atmospheric CO_2 concentrations trends (**a, c**) and daily rate of CO_2 change (**b, d**) in two independent experimental runs setup with scaled-down ratios of the terrestrial C cycle; n = 5.

Figure 1