Biotic feedback extends the life span of the biosphere

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Abstract

The Sun is becoming more luminous with time and will eventually overheat the biosphere. However, life cools the Earth by amplifying the rate of silicate rock weathering and maintaining a low level of atmospheric CO_2. Recent studies indicate a much stronger biotic weathering effect than in models used to estimate the life span of the biosphere. Here we show that the resulting feedback lengthens the survival of complex life by delaying the loss of CO_2 from the atmosphere. The weathering biota can potentially maintain the Earth in a habitable state when otherwise it would be too hot for them. If so, catastrophic warming rather than gradual CO_2 starvation will terminate complex life. Despite the possibility of an irreversible collapse, the current biosphere should remain resilient to carbon cycle perturbation or mass extinction events for at least 0.8 Gyr and may survive for up to 1.2 Gyr.

Introduction

If the biota exert a strong cooling effect on the climate and their growth is constrained to a restricted range of temperature, then the resulting feedback can maintain life under cool conditions long after increasing solar luminosity would have made a lifeless planet intolerably hot [*Watson and Lovelock,* 1983]. A number of biotic cooling mechanisms have been proposed for the Earth [*Lenton,* 1998; *Lovelock,* 1995], the best corroborated of which involves the biological amplification of silicate rock weathering [*Lovelock and Whitfield,* 1982; *Schwartzman and Volk,* 1989]. This liberates calcium and magnesium ions that can combine with dissolved CO_2 to form solid carbonate sediments, thus removing CO_2 from the atmosphere. An abiotic negative feedback was first proposed [*Walker et al.,* 1981] whereby increases in temperature accelerate the weathering reaction, thus sequestering CO_2 and tending to reduce its 'greenhouse effect' on climate. The rate of weathering is greatly amplified by a range of biological processes [*Schwartzman and Volk,* 1989] that respond to photosynthetic productivity. Productivity in turn depends on both CO_2 and temperature, strengthening the feedback on these variables [*Lenton,* 1998].

Vascular plants are particularly effective at rock weathering. In a study [*Bormann et al.,* 1998] accounting for the accumulation of weathered ions in vegetation and soil, experimental sandboxes at Hubbard Brook with red pine stands had weathering rates amplified by a factor of 10 for Ca^{2+} and 18 for Mg^{2+}, relative to plots with moss and lichen cover. Other studies summarised by *Moulton and Berner* [1998] generally underestimate weathering by not accounting for the accumulation of ions in soil or vegetation and soil. Correcting for these effects using available estimates of their magnitude [*Bormann et al.,* 1998] yields weathering amplification factors of > 7 for Ca^{2+} and > 38 for Mg^{2+}. An overall factor of ~ 7 for vascular plants has been used elsewhere [*Berner,* 1994]. Lichens also amplify weathering, with factors of 11 for Mg^{2+} and 4 for Si measured near Hubbard Brook [*Schwartzman,* 1999]. Hence the total weathering amplification due to land life is at least a factor of 10 and may exceed a factor of 100 [*Schwartzman,* 1999; *Schwartzman and Volk,* 1989].

Existing models used to estimate the life span of the biosphere [*Caldeira and Kasting,* 1992; *Franck et al.,* 2000] include a weak functional dependence of weathering rate on biological productivity, via its effect on soil pCO_2 and hence the activity of H^+ in soil freshwater (a_{H^+}). A 10-fold increase in soil CO_2 relative to the atmosphere is assumed [*Caldeira and Kasting,* 1992], which gives a 1.56 fold amplification of weathering rate due to the present biota. This is a significant underestimate, indicating that much of the observed biotic amplification of weathering is due to processes other than increased soil pCO_2 [*Schwartzman and Volk,* 1989].

Methodology

We altered existing models [*Caldeira and Kasting,* 1992; *Franck et al.,* 2000] to include a direct dependence [*Schwartzman and Volk,* 1989] of weathering rate, F_{wr}, on productivity, Π, with amplification factor, α:

$$\frac{F_{wr}}{F_{wr,0}} = \left(\left(1 - \frac{1}{\alpha}\right) \frac{\Pi}{\Pi_0} + \frac{1}{\alpha} \right) \left(\frac{a_{H^+}}{a_{H^+,0}} \right)^{0.5} \exp\left(\frac{T - T_0}{13.7} \right) \tag{1}$$

The dependencies of weathering rate on temperature, T (in K) and a_{H^+} (determined by soil pCO_2 and T) are unaltered. Hence the total biological amplification of weathering is $\beta = 1.56\alpha$, where α represents the amplification due to processes other than enhanced soil pCO_2. The productivity function from *Caldeira and Kasting* [1992] is representative of the photosynthetic organisms that drive weathering. Productivity is fertilised by CO_2 following Michaelis-Menten kinetics (a hyperbola), from zero at 10 ppm CO_2 (a lower limit for C_4 plants) with a half-saturation constant of 210.8 ppm. Productivity also depends on temperature following a parabola with optimum growth at 25°C and zero productivity at 0°C and 50°C. The upper limit is appropriate for most eukaryotes (but not some prokaryotes). Hence it is the current biosphere whose fate is considered, including complex life (large, multi-cellular eukaryotes). Vascular plants appeared on the land surface ~ 0.42 Gyr ago and their effect on weathering was well established by -0.35 Gyr [*Berner,* 1994].

Simulations are started at -0.5 Gyr. Increasing solar luminosity (S_{eff}, normalised to the present flux) forces the model systems. First we considered the 'geostatic' case [*Caldeira and Kasting,* 1992], in which sea floor spreading rate and continental area are held constant, then a 'geodynamic' case [*Franck et al.,* 2000], in which changes in continental area and sea floor spreading rate provide an additional forcing. In the geodynamic case, past continental growth is linearly extrapolated into the future and sea floor spreading rate is calculated to decline gradually throughout. Continental growth tends to increase the CO_2 sink while declining spreading rate slightly decreases the CO_2 source, both effects tending to decrease CO_2 with time.

Steady state solutions are derived using a root finding algorithm, which can detect multiple stable and unstable solutions when they coexist. 'Abiotic' solutions of the model correspond to zero productivity ($\Pi = 0$). 'Biotic' solutions of the model correspond to the stable state with $\Pi > 0$. In all cases, the biotic solution of the model at the present solar luminosity has a surface temperature of 15°C and atmospheric CO_2 of 320 ppm. Hence the biotic amplification factor α determines the abiotic state of the system. As α is poorly constrained, we have examined the sensitivity of the model behaviour to its value.

Results and Discussion

Fig. 1 shows the result for the geostatic model based on [Fig. 1]

Caldeira and Kasting [1992] with $\alpha = 20$, a tentative upper limit for the effect of biological processes other than enhancement of soil pCO_2, which gives $\beta \sim 31$ for the total amplification due to life. Both abiotic and biotic states of the Earth system are stable over a range of solar luminosity including the present. In this bi-stable regime, when life is removed it cannot recover automatically, because the abiotic Earth is uninhabitable to organisms with the assumed productivity response. The biosphere collapses catastrophically due to overheating in ~ 1.05 Gyr at $S_{eff} \sim 1.09$. Solar luminosity would then have to be decreased to $S_{eff} \sim 0.98$, the value ~ 0.2 Gyr ago, for complex life to be able to re-establish.

In earlier studies [*Caldeira and Kasting,* 1992; *Franck et al.,* 2000; *Lovelock and Whitfield,* 1982] the biosphere is predicted to perish gradually due to CO_2 starvation and there is no bi-stability. With $\alpha = 1$ we reproduce the result that CO_2 starvation will occur in ~ 0.85 Gyr [*Caldeira and Kasting,* 1992]. Strengthening biotic feedback (Fig. 2a) extends the future life span of the biosphere to a maximum of 1.22 Gyr for $\alpha = 4.4$. CO_2 starvation is delayed because declining productivity now causes a greater reduction in silicate weathering, thus tending to increase CO_2. For $\alpha > 4.4$ bi-stability occurs and the life span of the biosphere decreases slightly toward ~ 1 Gyr. The bi-stable regime appears earlier for larger α, covering the present luminosity for $\alpha > 18$, and extending to -0.5 Gyr for $\alpha \sim 23$.

The geodynamic model based on *Franck et al.* [2000] predicts higher temperatures in the past, a cooling trend through the present, and a temperature minimum in ~ 0.5 Gyr, before increasing solar luminosity generates a warming trend. Hence it can exhibit multiple bi-stable regimes (Fig. 2b). For $\alpha > 12.7$ a bi-stable regime appears within the past 0.5 Gyr, for $\alpha > 15.4$ it appears in the future as well, and for $\alpha > 21$ it extends throughout the model run. With $\alpha = 1$ we reproduce the prediction that the biosphere will die out in ~ 0.5 Gyr due to CO_2 starvation [*Franck et al.,* 2000]. Strengthening biotic feedback extends the future life span of the biosphere to a maximum of ~ 1.2 Gyr for $\alpha = 15.4$. A modest $\alpha = 6.3$ ($\beta \sim 10$) doubles the future life span to 1 Gyr.

When either the geodynamic or geostatic model is in a bi-stable regime, perturbation (Fig. 3) can cause a switch from the biotic to the abiotic state, but overheating above 45–50°C is necessary (the critical temperature corresponds to the unstable solution and varies with α and time). Under the current solar luminosity, if bi-stability occurs, the biotic state is stable to CO_2 perturbations of up to $\sim 2.4 \times 10^4$ ppm (Fig. 3a,b), which is an order of magnitude larger than the exploitable fossil fuel reserve. However, in ~ 0.8 Gyr an increase in atmospheric CO_2 of < 1000 ppm is sufficient to overheat the biosphere. This is of similar magnitude to the CO_2 perturbation expected in the next few centuries due to fossil fuel burning (which is occurring much faster than weathering feedback). Hence

if a species with the capacity to transfer large amounts of carbon to the atmosphere is present in 0.8 Gyr time it could threaten the persistence of the biosphere.

Reductions in productivity could also trigger biosphere collapse, but the 'critical fraction' required (Fig. 3c,d) must be sustained for long enough for CO_2 to reach the level that causes fatal overheating. Dividing the required change in CO_2 (Fig. 3a,b) by the input flux of CO_2 from volcanic and metamorphic degassing (currently $\sim 3.75 \times 10^{-2}$ ppm yr^{-1}) gives a minimum estimate of the time required. At present (if bi-stability occurs), it would take $\sim 5 \times 10^5$ yrs for sterilisation to cause an irreversible increase in CO_2 and temperature. Past mass extinction events removed up to $\sim 90\%$ of the species in the fossil record [*Raup and Sepkoski,* 1982], and after the K/T extinction the carbon cycle was perturbed for $1 - 3 \times 10^4$ yrs [*Kasting et al.,* 1986]. Larger and longer perturbations would have been required to reach a stable abiotic state if one existed in the past. However, the critical productivity perturbation declines sharply as the life span of the biosphere is approached, as does the time taken for critical CO_2 change, suggesting that future mass extinction events could trigger a switch to a hotter Earth.

The parameterisation of a water vapour saturated troposphere [*Caldeira and Kasting,* 1992] gives an upper estimate of the temperature change for a given CO_2 change. A less sensitive climate function would reduce the tendency for planetary bi-stability. However, the model neglects other biotic cooling mechanisms [*Lovelock,* 1995], which imply a warmer 'abiotic' planet than in our simulations and an increased tendency for planetary bi-stability. The results are also sensitive to changes in the productivity function [1].

Conclusions

The biotic amplification of weathering may be sufficiently strong to maintain the Earth in a habitable state when otherwise it would be uninhabitable to complex life [*Schwartzman and Volk,* 1989]. If so, the current biosphere will eventually collapse due to catastrophic overheating. However, it should persist for at least another 0.8 Gyr before becoming vulnerable to carbon cycle perturbation. Regardless of whether the Earth exhibits bi-stability, biotic feedback significantly prolongs the survival of the current biosphere up to a maximum of 1.2 Gyr hence. These results add a new dimension to the Gaia theory that the Earth is a self-regulating system [*Lenton,* 1998; *Lovelock,* 1995].

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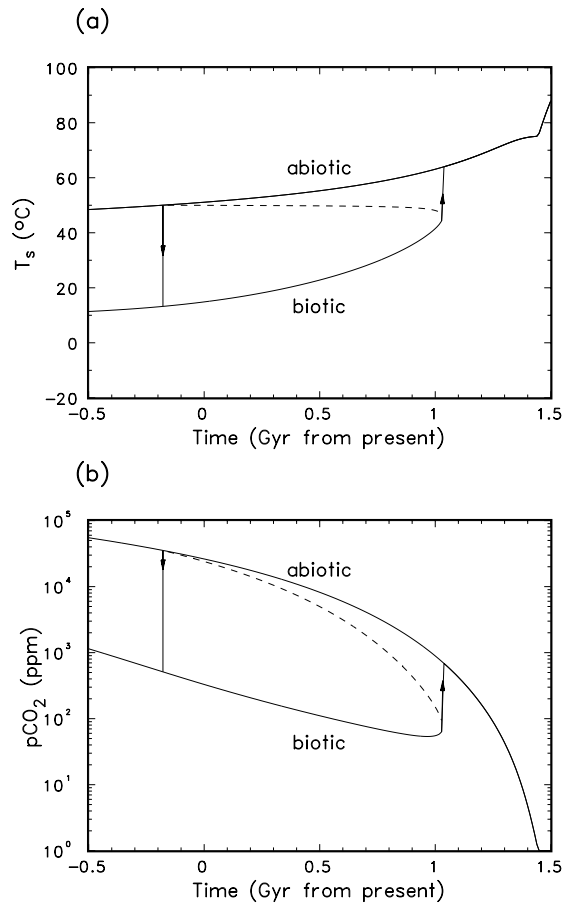
[1]Supporting data

Figure 1. State of the Earth with ('biotic') and without ('abiotic') the current biota. The model of Caldeira and Kasting was altered to include a factor of $\alpha = 20$ biotic amplification of weathering due to processes other than enhanced soil pCO_2, giving a total amplification factor of $\beta \sim 31$. Increasing solar luminosity forces the system. Evolution of: (a) surface temperature (T_s), (b) atmospheric CO_2.
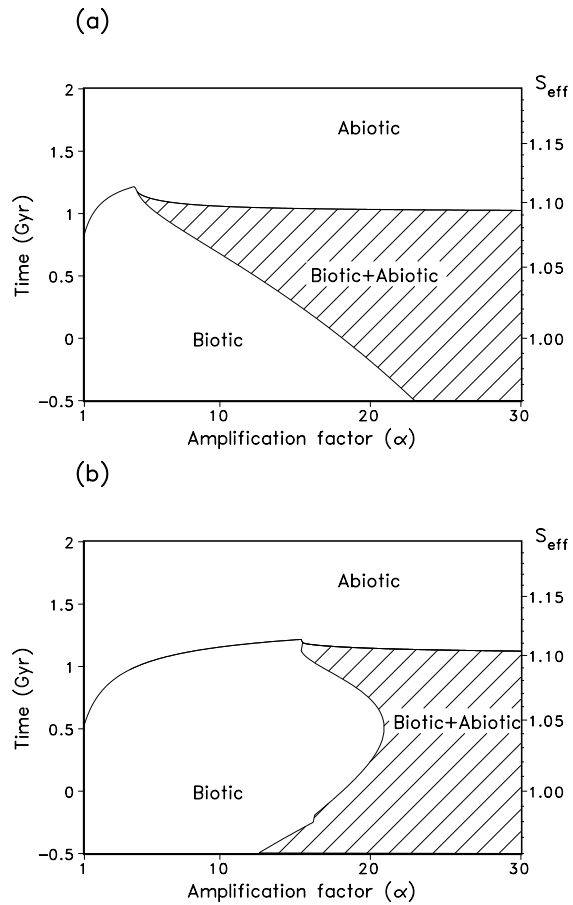
(a)

(b)

Figure 2. Earth system state as a function of biotic amplification factor (α) and time or corresponding solar luminosity (S_{eff}). Total biotic amplification of weathering is $\beta = 1.56\alpha$. In the 'Biotic' region, only the solution with life is stable. In the 'Abiotic' region, only the solution without life is stable. 'Biotic + Abiotic' indicates the bi-stable regime in which solutions with and without life are both stable. (a) Geostatic case. (b) Geodynamic case.
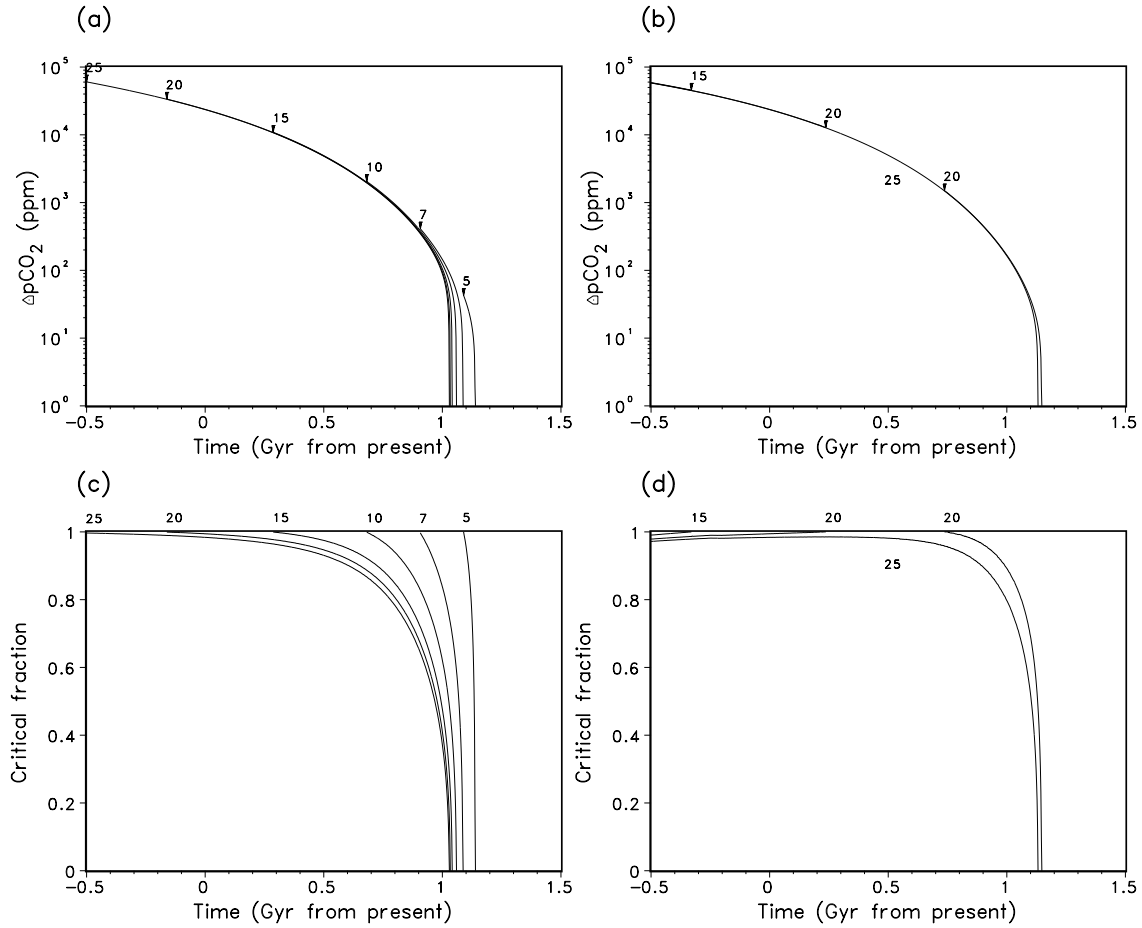
Figure 3. Critical perturbations required to switch the model Earth from a biotic to an abiotic state when both are stable. Solutions shown are for different indicated values of the amplification factor α. Top panels show the critical increase in atmospheric CO_2 for (a) geostatic case, (b) geodynamic case. Bottom panels show the critical fractional reduction in productivity for (c) geostatic case, (d) geodynamic case.