



Interactive comment on “The regulation of the air: a hypothesis” by E. G. Nisbet et al.

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We thank the referee for thoughtful and supportive comment.

The general observations are very helpful. The first is a request to spell out the argument and mechanism more fully. This is a general problem of cross-disciplinary work. How does one explain important but complex biochemical processes to earth science readership (and vice versa)? One reason Solid Earth was chosen for this paper was that the journal is open access, readily downloaded even in institutes whose libraries do not cross from life to earth. Thus it is important that the paper be accessible to both communities.

We shall respond as suggested, by rewriting the discussion of the function of rubisco

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and plant specificity, and also the idea of compensation points, in an attempt to make the topic more comprehensible to earth scientists.

The second point: the Gaia feedbacks: here we thank the referee for spotting an error. Lovelock and Whitfield (1972) is certainly cited in the text, but has fallen out of the references during our editing. We would be delighted to add further 'daisyworld' discussion. The evolutionary feedbacks are addressed in Figure 3, p 788. Over the very long timescales since rubisco's Form I evolved in the late Archaean, sustained feedback tuning of rubisco must have occurred, in the long aeons of co-evolution between rubisco, CO₂, O₂, and the greenhouse temperature.

As for the other ups, and downs of CO₂ through geological time, there are two scales of response to external changes, such as a sudden injection of CO₂ from a volcanic eruption. Immediately an injection occurs, the then-extant species respond very quickly. For example, since the 1980s, humanity has injected gigatons of C in CO₂ into the air each year. Very roughly half that injected C has already been removed, mainly by biological processes involving rubisco. This is a remarkably rapid removal, mostly mediated by photosynthetic draw-down in extant terrestrial and marine organisms.

Then, as CO₂ changes, there will be evolutionary response: those organisms will be favoured that have less specific, faster-acting rubisco. The example of the PETM suggests that full reequilibration after a major excursion comparable to the modern CO₂ injection is achieved in about 100-150 ka. This reequilibration would have involved competitive selection of rubisco specificities between different plants. Over multi-generational time, land plant and plankton rubiscos compete, and selection will fine-tune them for competitive advantage.

Interestingly, a cool ocean is favourable for many ocean plankton, as CO₂ is more soluble in cold water, and their rubisco can reflect this. On land, the C₄ adaptation (e.g. grasses), pre-processing the CO₂, favours C₄ plants in low CO₂ (glacial) episodes. C₃ plants, on the other hand, succeed in warm (higher CO₂) and thus wet interglacials.

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This evolutionary response to external shock can stabilise new evolutionarily stable planetary biological communities, but at a different CO₂ level for optimised maximum productivity.

The referee comments that the long-term burial of carbon seems to be not so much under biological control, as a product of major tectonic and other patterns. Indeed so, but that is not to remove the necessity of biology. If large amounts of carbon are removed from the atmosphere by burial, the reduction of the atmospheric CO₂ content will induce a biological feedback response, by selective pressure to re-optimize rubisco's compromise between CO₂:O₂ specificity and the rate of catalytic turnover. On the modern planet a reduction in atmospheric CO₂ will favour C₄ plants, that use a pre-concentration mechanism to present CO₂ to rubisco. Since the start of the Holocene, immense amounts of carbon have been sequestered in Siberian and Canadian peats (Smith et al. Siberian peatlands. . .Science, v303, p354-356 suggest >70 PgC in Siberia alone), yet the atmospheric greenhouse has remained surprisingly stable, in part because the increased rate of burial may also lead to an increased rate of methane emission.

The view that rubisco sets the atmospheric CO₂:O₂, and hence also the atmospheric greenhouse, the planetary surface temperature, and ocean pH, is not incompatible with the geo-environmental and geochemical responses. Biology acts quickly, and thus kinetics set the surface conditions such as pH and T, and rainfall acidity and intensity. Those biologically set conditions then constrain the geochemical response. Geochemistry acts and the Urey cycle operates, but under the pH and T constraints set by rubisco. This point is discussed further in response to other comments. More generally, we are not arguing for a static unchanging atmospheric CO₂ content, but rather for an evolutionarily stable strategy (Smith and Price, Nature 246, 15-18, 1973) - a feedback system (see Fig. 3), in which natural selection responds to change in such a way as to maintain the optimization of rubisco Tcherkez et al., 2006) and hence the biosphere's productivity.

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Finally, we thank the referee for very thoughtful and perceptive comment.

Interactive comment on Solid Earth Discuss., 3, 769, 2011.

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