General reply to reviewer's comments on "Assessing life's effects on the interior dynamics of planet Earth using non-equilibrium thermodynamics" by J. G. Dyke, F. Gans and A. Kleidon.

We feel did not sufficiently explain our main hypothesis. We do not argue that life has had a unidirectional effect on continental crust dynamics. For example, we find the hypothesis proposed by Rosing et al (2006), that it was the evolution of oxygenic photosynthesis that led to a significant increase in the production of continental crust, as being consistent with our study. What we seek to do is take the first quantitative steps towards assessing how life's effects may manifest themselves on geological processes. In this manuscript we have focussed on life's effects on the flux of continental crust to the oceans which in turn can affect upper mantle temperature, oceanic crust recycling and outgassing of volatiles such as CO_2. We attempted to demonstrate that at a fundamental thermodynamic level, these systems are coupled and can exchange mass and energy across their boundaries. If life affects these boundary conditions, then it's effects may penetrate the Earth's crust.

Following on from some of the reviewer's comments, we revisited the continental crust model and discovered an error. We have included a short appendix to the manuscript that shows how an important uplift friction parameter was obtained. The new solutions for the model include a timescale of continental crust erosion of two million years and a new value for sea floor spreading of 2.84 cm/yr. We discuss these new results in the specific replies to ESDD-1-C135-2010 reviewer's comments.

We took on board the comments that a more quantitative discussion was required. To that end we have produced a new set of results that gives values for the changes in the rate of oceanic crust recycling and outgassing of CO_2 in response to the complete removal of biological enhancement of weathering of continental crust. We show that if the diffusivity parameter in the oceanic crust recycling model remains fixed, then the removal of biologically enhanced weathering leads to an increase in sea floor spreading to 2.89 cm/yr and an increase in outgassing to CO_2 to 1.42×10^{10} g/yr. This is 2×10^{8} g/yr more than estimates for the current Earth. However, if we allow the diffusivity parameter to vary so that the oceanic crust system relaxes back into a state which generates maximum rates of power, then the removal of biologically enhanced weathering leads to a *decrease* is oceanic crust recycling to 2.61 cm/yr and a *decrease* in outgassing of CO_2 to 1.28×10^{10} g/yr. This is 1.2×10^{9} g/yr less than estimates for the current Earth. We explain these results in the specific replies to ESDD-1-C149-2011 reviewer's comments.

By formulating the models as non-equilibrium processes, we are able to apply the principle of Maximum Entropy Production in order to provide upper limits for the power generated and dissipated and so their maximum rates of entropy production. This approach does not require the detailed formulation of processes. For example, our model of mantle convection contains no information as what the mantle is primarily composed of. We would argue that given the information to hand such information is not necessary for the prediction of maximum rates of work. For the three models of mantle convection, oceanic crust recycling and continental crust uplift & erosion we identify a 'tunable' parameter that affects the rates of power generation for these systems. Adjusting these parameters so that these systems generate maximum rates of power (and so entropy production at steady state) leads to reasonable estimates for: temperature profiles within the mantle, continental crust thickness, oceanic crust recycling rates and global rates of erosion. We have made changes to the manuscript title, abstract, introduction and discussion sections in order to better explain this motivation. The new title and abstract are:

New Title:
Towards understanding how surface life can affect interior geological processes: A non-equilibrium thermodynamics approach.

New Abstract:
Life has significantly altered the Earth's atmosphere, oceans and crust. To what extent has it also affected interior geological processes? To address this question, three models of geological processes are formulated: mantle convection, continental crust uplift & erosion, and oceanic crust recycling. These processes are characterised as non-equilibrium thermodynamic systems. Their states of disequilibrium are maintained by the power generated from the dissipation of energy from the interior of the Earth. It is shown that altering the thickness of continental crust via weathering and erosion affects upper mantle temperatures which leads to changes in rates of oceanic crust recycling and consequently rates of outgassing of carbon dioxide into the atmosphere. Estimates for the maximum possible power generated by various elements in the Earth system are shown. This includes, inter alia, surface life generation of 215TW of power, a magnitude greater than those of geological processes such as mantle convection at 12TW. This high power results from life's ability to harvest energy directly from the sun. Life need only utilize a small fraction of the generated free chemical energy for geochemical transformations at the surface, such as affecting rates of weathering and erosion of continental rocks, in order to affect interior, geological processes. Consequently when assessing the effects of life on Earth, and potentially any planet with a significant biosphere, dynamical models may be required that better capture the coupled nature of biologically mediated surface and interior processes.

References

Rosing, M., Bird, D., Sleep, N., Glassley, W., and Albarede, F. (2006). The rise of continents: An essay on the geologic consequences of photosynthesis. Palaeogeography, Palaeoclimatology, Palaeoecology, 232(2):99–113.