

The wildfire factor

David Schimel and David Baker

Events such as wildfires, occurring on a tiny area of the globe, can have a huge impact on the global carbon cycle. This much is plain from investigation of the terrible fires that afflicted Indonesia five years ago.

In 1997–98, the growth rate of carbon dioxide in the atmosphere doubled, reaching the highest on record. As even casual television viewers could have guessed, a contribution to the increase might have come from the wildfires occurring in Indonesia at that time, which burned for months and were widely shown around the world. On page 61 of this issue¹, Page *et al.* go beyond guesses, and calculate that in fact much of the inferred increase in atmospheric CO₂ can be accounted for by these fires. The authors estimate the emissions to have been 0.8–2.6 × 10¹⁵ grams — petagrams (Pg) or gigatonnes — of carbon. This is equivalent to 13–40% of the annual emissions from anthropogenic fossil-fuel combustion.

Page *et al.* used satellite imagery and field measurements for Indonesia to estimate the burned areas and carbon losses. The burned areas included vast deposits of peat, in some cases 20 m thick, which had lost between 25 and 85 cm of their depth through fire. Most of the carbon released came from this source, not from the burning of forest trees. To put the size of the emissions from these fires in another way, they were comparable to the global carbon uptake by the terrestrial biosphere in a typical year — yet they came from a relatively tiny area of the globe.

In a parallel study in *Global Biogeochemical Cycles*², Langenfelds *et al.* used atmospheric measurements to investigate the effects of biomass combustion on the global carbon cycle. They estimated the proportion of CO₂ released by fire from the ratios of hydrogen, methane and carbon monoxide. Fire emits these other gases in relatively consistent ratios, so CO₂ combustion emissions can be derived from measuring them. Langenfelds and colleagues' approach cannot identify precisely where the fires occurred, but it does implicate fire as a significant contributory factor to changes in CO₂ emissions. Their estimate of the amount released in 1997–98 (0.8–3.7 Pg C) overlaps with the figures calculated by Page *et al.*¹. Together, these two papers provide strong evidence that the Indonesian wildfires made a large contribution to the leap in atmospheric CO₂ levels in 1997–98.

Rough confirmation of both the magnitude and location of the carbon emissions comes from a different approach again — spatial analysis of global CO₂ concentrations in the atmosphere, which we have used to

compile Fig. 1. Sources and sinks of CO₂ are estimated from observed spatial patterns and temporal changes in atmospheric CO₂, using the approach known as inverse modelling³. By itself, this approach can provide only tentative conclusions, and so Fig. 1 shows the results we obtained using different subsets of observations and different amounts of 'smoothing' to bracket the range of possible answers. The existence of a large emission in Southeast Asia, of the order of 1 Pg C, appears in all combinations of the estimation techniques and data used. So, although the figures produced by Page *et al.* appear to be extraordinarily large, they are supported by independent approaches.

But why were the fires in Indonesia so serious? It took a combination of climate change — specifically, drought, caused by the 1997–98 El Niño event — and changes in

land use brought about by human agency. Drought-induced fires are common in the tropics, and also affect other parts of Australia and Amazonia. But in Indonesia their intensity and duration, and the damage wrought, were all the more severe because small clearings and channels associated with logging operations allowed the vegetation and soils to dry out, making them more susceptible to burning. Because of the thickness and high carbon density of the peat, the carbon emissions from the fires were extremely high.

This all points to a general challenge for those studying the carbon cycle. Detecting the subtle and fine-grained effects of land-use change, such as that occurring in Indonesia and elsewhere, requires satellite imagery of 30-m resolution. This is far beyond the reach of today's models of the terrestrial carbon cycle, which have 50-km resolution, at best. Future work to understand and predict the system's behaviour must take account of how land use can be a factor in fire and other disturbances. Changed land use,

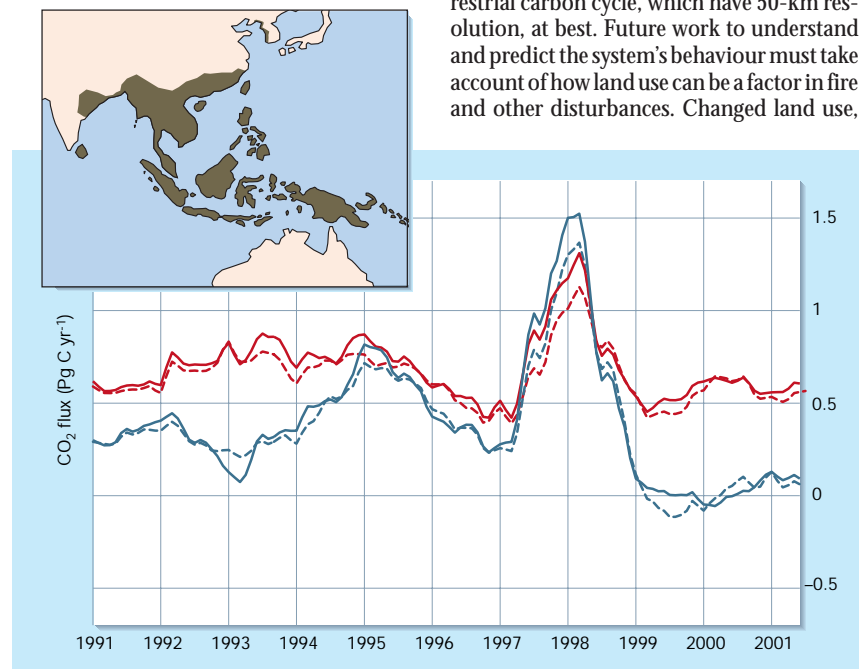


Figure 1 The CO₂ pulse of 1997–98 from Southeast Asia. Page *et al.*¹ estimate that, in releasing 0.8–2.6 Pg C during this time, wildfires in Indonesia were responsible for much of the increase in levels of atmospheric CO₂. Atmospheric modelling supports this view, as depicted here. Our global analysis reveals a large emission in Southeast Asia, and is the average of ten models³, each run with two data sets and different degrees of smoothing. Red lines show data⁶ from 97 monitoring stations; blue lines are data from a subset of 90 stations, omitting seven in the South China Sea. Dashed and solid lines show different degrees of smoothing of the variability in ocean fluxes. The land areas in Southeast Asia defined in the atmospheric model are shown by the shaded area of the inset map. The Indonesian fires were probably only part of the response of the global carbon cycle to the El Niño of that period, as other tropical land regions also show high emissions during 1997–98 in this modelling analysis.

and the subsequent environmental perturbation, can help to bring about both abrupt emissions of CO₂ and long-lasting alterations in ecosystem structure and function.

The need to understand such abrupt change is pressing. For decades, carbon-cycle researchers have analysed observations of atmospheric CO₂ in terms of processes such as ocean CO₂ uptake, and photosynthesis and respiration by land plants. These processes are assumed to operate continuously and relatively smoothly in time and space. Analytical approaches such as inverse modelling tend to assume that the same processes are operating at all times⁴. Despite the advent of so-called 'dynamic global vegetation models', modelling remains dominated by simulations of photosynthesis and respiration, with only primitive representations of combustion⁵.

The results of Page *et al.*¹ make it clear that abrupt events can have an appreciable effect on the carbon cycle. The fires in Indonesia

were not only episodic in time, they occurred on a relatively small part of the Earth's land surface. Most observing systems and modelling strategies assume that, to affect the carbon cycle, processes must occur over thousands of square kilometres or more. But especially in areas of high carbon density, catastrophic events affecting small areas can evidently have a huge impact on the global carbon balance. ■

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Vision

What is a naked retina good for?

Michael F. Land

The crab *Bythograea thermydron* has eyes that consist of large naked retinas. Studies of the crab's larval forms suggest that these eyes are a specific adaptation to the dim environment of oceanic volcanic vents.

Along the mid-ocean ridges of the Atlantic and Pacific are volcanic vents from which water emerges at temperatures of up to 350 °C, more than three times the boiling point at the surface. This heat, and the minerals that emerge with the water, supports a diverse fauna, including a number of crustaceans with very unusual eyes. On page 68 of this issue, Jinks and colleagues¹ take our understanding of these optical systems further, and their results provide clues to the light environment around vents.

The shrimp *Rimicaris exoculata* was the first vent crustacean with unusual eyes to be described². Here, the optics of the compound eye, which allow images to be resolved, have disappeared and been replaced by an extended naked retina much larger than the eyes of related species. But did this peculiar arrangement evolve through degeneration, caused by the absence of light in the deep ocean (the vents are several kilometres below the surface)? Or is it a specific adaptation to the radiation environment around the vents (Fig. 1)? One approach to this problem is to look at the development of these eyes as the animal changes from larva to adult. If the eye starts out as a normal compound eye, then this strengthens the argument that the later naked retina is a specific adaptation to the vent environment: otherwise, why go to the trouble of making

one structure, then unmaking it and effectively replacing it with something else?

This is the approach that Jinks *et al.*² have taken in their studies of the crab *Bythograea thermydron*. Adults of this species inhabit vents and have naked retinal structures similar to those of *Rimicaris*. Crucially, several other stages in the life cycle are also known, including early ('zoea') larvae, which live not in vents but as deep-sea plankton. Studying



Figure 1 Deep-sea volcanic vent — home to species such as the crabs studied by Jinks *et al.*¹.

crabs reared from egg-bearing females, the authors found that these planktonic larvae have normal apposition compound eyes, which progressively lose their optics during development and turn into the naked, rather amorphous, retina of the adult.

The pigments in the eye that respond to light also change: they are maximally sensitive to blue light (447 nm) in the planktonic zoea larvae; to blue-green light (479 nm) in the later megalopa larvae, which already inhabit vents; and finally to longer-wavelength blue-green light (489 nm) in the adult eye. What is striking here is that this change is the opposite of what one might expect. Surface light has most energy in the green region of the spectrum, but, with increasing depth, scattering and absorption reduce the transmitted light to a narrow waveband in the blue, around 470 nm. Visual pigments usually reflect this change.

So Jinks and colleagues' finding that *Bythograea* shows the opposite trend with depth suggests that there might be something interesting about the composition of the light — such as it is — around the vents. It was originally thought that there was just enough short-wavelength energy in the black-body radiation from the vent water itself to provide a few photons that would allow a green-sensitive pigment to detect something. But more recent measurements suggest that there is still more light in the visible range³. Sulphide oxidation can cause chemiluminescence in the visible range, and there are several other more exotic physical phenomena that might also contribute. Whatever the origin of vent light, however, it seems that there is enough for rudimentary vision with a non-resolving retinal structure.

This raises another question: why have an eye with no optics? Clearly, a bare retina cannot determine the direction of light to better than the nearest hemisphere — in front of the animal or behind it. The gain, in abandoning the machinery of resolution, is sensitivity.

The amount of light available to a detector from a given source of light is proportional to the area of the aperture of the detector, and the size of the cone (solid angle) over which light is received⁴. In a shore crab, the area of the aperture of each eye facet is about 0.001 mm², and the solid angle over which the receptors accept light is about 3 square degrees. For adult *Bythograea*, if the whole eye is viewed as a single detector, the aperture area is about 1 mm², and the acceptance cone is a hemisphere (20,626 square degrees). The overall sensitivity ratio between the naked retina and the proper eye is then about 7 million to 1. If what is required is a non-directional photocell, used for example to establish proximity to a vent, then a naked retina makes very good sense.

Naked retinas are not confined to vent