

between about 0.75 and 1.0. That's why the work by Venkatasubramanian and co-workers¹ is so interesting: they report a ZT of 2.4 in thin films of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ semiconductors. These materials appear to achieve such high ZT s thanks to their unusual structure — a superlattice formed by alternating layers of semiconductors. The previous record for ZT at room temperature was held by a bulk semiconductor alloy based on Bi_2Te_3 and Sb_2Te_3 . The superlattice structure appears to enhance the transport of current-carrying electrons (and holes) while inhibiting transport of heat-carrying phonons (quantized vibrations of the crystal lattice). Both effects boost ZT .

When the modern era of thermoelectric science and technology began to emerge in the late 1950s, it seemed possible that thermoelectrics might approach the efficiency of mechanical refrigerators and power generators. By the 1970s, given the lack of progress, few thought it likely. There was even speculation that a ZT of 1 represented some sort of thermoelectric barrier. Certainly it was an empirical limit that nearly halted research and development. But in the early 1990s Rudolph Buser, then associated with the United States Army Night and Electro-Optics Directorate, called on scientists to re-examine thermoelectrics. A basic science programme to increase ZT was soon underway, with support principally from the US Navy's Office of Naval Research and DARPA (Defense Advanced Research Projects Agency). By the late 1990s there was some progress, but even then you had to be an optimist to believe the barrier had been broken².

With the results of Venkatasubramanian *et al.*¹, even sceptics and dispassionate observers can safely be encouraged. The material properties, as measured by the figure of merit ZT , are 2.5 times better than the current state of the art, have been verified by more than one method, and are useful at room temperature. It has been a long time in coming but any conjecture about a thermoelectric barrier of $ZT = 1$ seems to have been safely put to rest.

Is it time to replace your old-fashioned fridge? Not just yet. As promising as these new results are, the efficiency (estimated from ZT) remains significantly less than that of conventional refrigerators. And there is no telling when, or if, costs and various engineering issues can be resolved.

On the other hand, this result may be good enough to greatly expand the range of practical applications. After all, modern manufacturers are good at reducing costs and there is no reason to believe this is the last word in efficiency. And most physicists can remember when the upper limit for superconducting transition temperatures was rather firm at about 23 K (-250°C), whereas the record now stands at 164 K (-109°C) — still pretty cold, but few would now bet against it going higher. Experimentalists just love to prove theorists wrong. ■

Cronin B. Vining is at ZT Services, 2203 Johns Circle, Auburn, Alabama 36830-7113, USA.
e-mail: nature@zts.com

1. Venkatasubramanian, R., Siivola, E., Colpitts, T. & O'Quinn, B. *Nature* **413**, 597–602 (2001).
2. Dubois, L. H. *18th International Conference on Thermoelectrics* 1–4 (IEEE, Piscataway, New Jersey, 1999); <http://www.zts.com/darpa/dubois99>

Global change

Matter of time on the prairie

Lindsey Rustad

In some ecosystems at least, extrapolating from the short-term effects of global warming will give a misleading impression of the reaction over longer periods of time.

The Earth is warming. Given that CO_2 seems to be the main determinant of global temperature, predictions of climate conditions in the future depend in part on gauging the response of the carbon cycle to warming. This is a question that Luo *et al.* address on page 622 of this issue¹. In their experiments on a terrestrial ecosystem in Oklahoma, they find that, in this case at least, acclimatization to increased temperature means that feedback of CO_2 into the atmosphere in the long term would be less than expected.

Over the past century, the Earth's mean surface temperature has increased by 0.6°C . During the next 100 years, it is predicted to increase by a further 1.4 to 5.8°C , and by even

more at higher latitudes². This predicted rate of change is unprecedented in at least the past 10,000 years, and is largely attributed to increases in the greenhouse gases, most notably CO_2 , resulting from the burning of fossil fuels and changes in land use. Confidence in these predictions is increasing, but considerable uncertainties remain. We can't even be sure whether terrestrial ecosystems will take up atmospheric CO_2 (and so moderate further increases in temperature), or be a source of it (and so drive temperature even higher).

In predictions of these climate–ecosystem interactions it is often assumed that, if moisture and nutrients are not limiting factors, rates of both photosynthesis (which removes

CO_2 from the atmosphere) and respiration (which releases CO_2 to the atmosphere) will increase with increasing temperature in a predictable way that will remain constant over time. Luo and colleagues¹ tested whether this assumption applies to soil respiration — the combined respiration of roots and micro- and macro-organisms in the soil. They used infrared heaters to warm plots of tall grass prairie by about 2°C over a period of one year, and compared these plots with unheated control plots. Although soil respiration was expected to increase by 15–20%, there was no significant change. The authors attribute this to respiratory acclimatization to the warmer temperatures: as temperatures rise, they suggest, the sensitivity of respiration to increased temperature decreases, thereby weakening terrestrial feedback to global warming.

A similar conclusion was reached recently by Xu and Qi³, who studied a forest in the Sierra Nevada. In their study, which took advantage of spatial and seasonal variations in soil respiration, the sensitivity of soil respiration to increased temperature was lowest in the summer, when temperatures were highest. But in this case it was difficult to distinguish the effects of higher temperature and lower soil moisture.

These authors' emphasis on soil respiration is entirely appropriate because it constitutes the second largest pathway in the global carbon cycle, second only to gross primary productivity. Global estimates^{4,5} of soil respiration are in the range 68 – 100 Pg C yr^{-1} (Pg being petagrams, 10^{15} g); to put this in perspective, the annual input of CO_2 to the atmosphere through human activities is about 7 Pg C yr^{-1} . Evidently, then, even a small increase in soil respiration could accelerate climate change in the twenty-first century; conversely, a small decrease could compensate for anthropogenic emissions, and so slow the expected rate of change.

It has long been known that there is a strong link between soil temperature and soil respiration — respiration increases with rising temperatures, and vice versa^{5–7}. A standard way of defining this relationship is to calculate the Q_{10} value, which is the increase in respiration for each 10°C rise in temperature. Reported Q_{10} values⁵ for soil respiration are typically in the range 1.3–3.3, with a mean of about 2.4. But although the concept is a useful one, care is needed in using Q_{10} relationships to infer long-term trends: they are relatively simplistic, and are derived largely from laboratory experiments or short-term field studies of five years or less.

Unlike photosynthesis, soil respiration is not a single process. Rather, it is the summed activity of a complex and changing assemblage of below-ground organisms, including roots, microflora and micro- and macrofauna. These organisms respond not only to

changes in temperature, but also to changes in moisture, nutrient availability and substrate quality, all of which are also directly or indirectly affected by temperature. For instance, the predicted relationships between soil temperature and soil respiration do not hold when moisture becomes limiting^{8–10}, or when there is a shift in the composition of the microbial community¹¹, or when there is a change in substrate quality or quantity^{12,13}.

The Harvard Forest soil warming experiment in Petersham, Massachusetts, provides a useful example of this latter case. In this study¹², the researchers found that soil respiration increased in response to experimental warming. Soil respiration was 40% greater in warmed plots than in control plots during the first year of the experiment, the rise probably being fuelled by the microbial oxidation of labile (easily decomposed) carbon compounds. The magnitude of the response of soil respiration to experimental warming declined markedly in the second year, however, presumably because the labile carbon supply was depleted. If a Q_{10} value from the first year of data had been used to extrapolate results and predict longer-term respiratory responses to warming, it would have resulted in a large overestimate of the amount of carbon released from the forest soil, and so of the potential feedback to climatic warming.

Luo and colleagues¹ likewise find a decline in the temperature sensitivity of soil

respiration with warming: the Q_{10} was 2.70 in the unheated plots compared with 2.43 in the heated plots. As with the Harvard Forest example, the results show that caution should be used in extrapolating results from short-term experiments to predict longer-term responses to environmental perturbations such as warming. The question of how ecosystems might or might not acclimatize to a warmer world bears serious consideration. But as with much research on this topic, longer time series of data will be needed to provide plausible answers. ■

Lindsey Rustad is in the US Department of Agriculture Forest Service, Northeastern Research Station, 271 Mast Road, Durham, New Hampshire 03824, USA.

e-mail: rustad@maine.edu

1. Luo, Y., Wan, S., Hui, D. & Wallace, L. L. *Nature* **413**, 622–625 (2001).
2. Intergovernmental Panel on Climate Change *Climate Change 2001: The Scientific Basis* (Cambridge Univ. Press, 2001); <http://www.ipcc.ch>
3. Xu, M. & Qi, Y. *Glob. Biogeochem. Cycles* **15**, 687–696 (2001).
4. Musselman, R. C. & Fox, D. G. *J. Air Waste Mgmt Assoc.* **41**, 798–807 (1991).
5. Raich, J. W. & Schlesinger, W. H. *Tellus* **44**, 81–89 (1992).
6. Rustad, L. E. *et al. Oecologia* **126**, 543–562 (2001).
7. Kirschbaum, M. *Soil Biol. Biochem.* **27**, 753–760 (1995).
8. Salesk, S. R., Harte, J. & Torn, M. S. *Glob. Change Biol.* **5**, 125–141 (1999).
9. McHale, P. J., Mitchell, M. J. & Bowles, F. P. *Can. J. Forest Res.* **28**, 1365–1372 (1998).
10. Rustad, L. E. & Fernandez, I. J. *Glob. Change Biol.* **4**, 597–607 (1998).
11. Zogg, G. P. *et al. Soil Sci. Soc. Am. J.* **61**, 475–481 (1997).
12. Peterjohn, W. T. *et al. Ecol. Appl.* **4**, 617–625 (1994).
13. Holland, E. A. *et al. Glob. Change Biol.* **1**, 115–123 (1995).

Ion channels

Swimming with sperm

David L. Garbers

Mice become infertile if they lack the gene encoding a newly discovered sperm-specific ion channel. Sperm are produced in normal quantities, but have trouble moving.

Spermatozoa rely on calcium ions to function. And, like the cells from which they are produced, sperm seem to express several channels that allow calcium ions to enter¹. But, so far, none of these ion channels has been linked to the regulation of sperm motility. That changes with an impressive paper by Ren and colleagues², published on page 603 of this issue. The authors have discovered a channel, which probably allows calcium ions to pass through, that is expressed only in sperm and is needed for them to move normally.

When sperm are first produced in the testes they are immobile (Fig. 1, overleaf). It is only after they are moved to their storage site, the epididymis, that they acquire the ability to swim forwards (progressive motility) — a behaviour that is required for successful fertilization. Sperm do not actually move about in the epididymis, but

actively swim forwards after ejaculation or dilution into various media. As they enter the isthmus of the female reproductive tract, sperm slow down once more³. They resume their migration when ovulation occurs, eventually reaching the ampulla region of the oviduct, where fertilization takes place.

As well as acquiring the ability to move progressively, sperm must undergo a further maturation process, termed capacitation, before they can fertilize an egg. This occurs while they are in the female reproductive tract, and results in two changes in sperm behaviour. First, they become able to undergo an acrosome reaction in response to the egg's extracellular matrix (zona pellucida), which involves the release of matrix-digesting enzymes. Second, sperm motility is hyperactivated.

Cyclic nucleotides, Ca^{2+} ions and intra-

cellular pH have been all proposed to regulate progressive motility and the events associated with capacitation, including the change to 'whiplash' hyperactivated motility³. Spermatozoa express voltage-gated Ca^{2+} channels, cyclic-nucleotide-gated channels and transient receptor potential channels (a different type of putative Ca^{2+} channel)^{1,4}. Yet the role of all of these in sperm function has remained elusive, in part because it has not been possible to study sperm by patch-clamping, a central technique for investigating ion channels. Ren *et al.*² had similar difficulties with patch-clamping, but a variety of other experiments suggest that the channel they identified — which they dub 'CatSper' — is probably a Ca^{2+} -specific cation channel, and is certainly needed for normal sperm motility.

CatSper is the prototype of a new ion-channel family, described by the authors and by members of my laboratory in another paper⁵. The proteins in this family are something of an oddity. Channels such as the voltage-gated K^+ channels consist of a single subunit, or 'repeat', which comprises six membrane-spanning portions and has a voltage sensor and an ion-selectivity pore. The common voltage-gated Na^+ and Ca^{2+} channels consist of four such repeats. The CatSper^{2,5}, by contrast, have a single repeat, but the ion-selectivity pore is similar to that in each repeat of the voltage-gated Ca^{2+} channels. CatSper probably forms part or all of a tetrameric cation channel². Unfortunately, however, the ion selectivity of CatSper remains formally unproven: experimental expression of the protein alone or with other channel subunits resulted in no detectable ion-channel activity^{2,5}.

Nevertheless, the fact that CatSper is expressed only in male germ cells — specifically, in the tails of mature sperm — was a strong hint that it is involved in regulating sperm motility. Indeed, Ren *et al.* show that CatSper is required for normal progressive motility, and that its absence renders mice infertile. This represents a step towards understanding how ion channels regulate sperm motility. It also provides an opportunity to test the role of different forms of motility in fertilization. Sperm from CatSper-deficient mice swim with a progressive velocity about one-third that of normal. They can fertilize eggs whose extracellular matrix has been removed but not those with an intact matrix, so it seems that the reduction in progressive motility is sufficient to block penetration of the zona pellucida. Alternatively, the sperm might also fail to acquire the hyperactivated form of motility (a possibility that has not yet been tested).

The molecular details of how CatSper works remain unknown. Animals lacking CatSper produce normal quantities of morphologically normal sperm, so it probably