

membrane-spanning domains, which was first observed in the calcium pump¹¹. In LeuT_{Aa}, TM1 and TM6 are antiparallel to each other, and have breaks in their helical structure approximately halfway across the membrane (Fig. 1). These breaks expose main-chain carbonyl oxygen and nitrogen atoms for hydrogen bonding and ion binding. Residues on TM3, TM7 and TM8 also contribute to the binding of sodium and leucine. Some of these residues had already been implicated in ion and/or substrate binding by functional studies of mutants of several of the neurotransmitter transporters (cited in ref. 1). Therefore, it appears that the structure reported by Yamashita *et al.* is a physiologically relevant conformation of the transporter.

In this structure, the binding pocket is occluded — the external and internal gates are closed. Two ion pairs, one between the extracellular ends of TM1 and TM10 and the other between the intracellular ends of TM1 and TM8, contribute to these gates (Fig. 1). The crystal of LeuT_{Aa} also contains a chloride ion (not shown on the figure), but this is not located in the binding pocket. Indeed, in LeuT_{Aa}, leucine transport is dependent on sodium but not on chloride¹. In contrast, in GAT-1, another member of the family, the neurotransmitter GABA is transported together with sodium and chloride ions¹². So although the overall structure of the neurotransmitter transporters is expected to be similar to that of LeuT_{Aa}, there will be variations.

In the future, the LeuT_{Aa} structure will be useful in designing drugs that specifically inhibit the neurotransmitter transporters. Obtaining more 'snapshot' structures representing different transporter conformations will shed light on the most fundamental question: which conformational changes occur during the transport cycle? Or, in terms of the 'lock' model, how is the opening of the external gate coupled to the closing of the internal one, and vice versa? ■

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1. Yamashita, A., Singh, S. K., Kawate, T., Jin, Y. & Gouaux, E. *Nature* **437**, 215–223 (2005).
2. Jardetzky, O. *Nature* **211**, 969–970 (1966).
3. Guastella, J. *et al. Science* **249**, 1303–1306 (1990).
4. Pacholczyk, T., Blakely, R. D. & Amara, S. G. *Nature* **350**, 350–354 (1991).
5. Abramson, J. *et al. Science* **301**, 610–615 (2003).
6. Huang, Y., Lemieux, M. J., Song, J., Auer, M. & Wang, D.-N. *Science* **301**, 616–620 (2003).
7. Yernool, D., Boudker, O., Jin, Y. & Gouaux, E. *Nature* **431**, 811–818 (2004).
8. Hunte, C. *et al. Nature* **435**, 1197–1202 (2005).
9. Hama, H. & Wilson, T. H. *J. Biol. Chem.* **268**, 10060–10065 (1993).
10. Zhang, Y. & Kanner, B. I. *Proc. Natl Acad. Sci. USA* **96**, 1710–1715 (1999).
11. Toyoshima, C., Nakasako, M., Nomura, H. & Ogawa, H. *Nature* **405**, 647–650 (2000).
12. Keynan, S. & Kanner, B. I. *Biochemistry* **27**, 12–17 (1988).

ENVIRONMENTAL SCIENCE

Carbon unlocked from soils

E. Detlef Schulze and Annette Freibauer

Changes in climate and land use are implicated as the main factors in the large-scale loss of carbon from soils in England and Wales over the past 25 years. The same picture is likely to apply much more broadly.

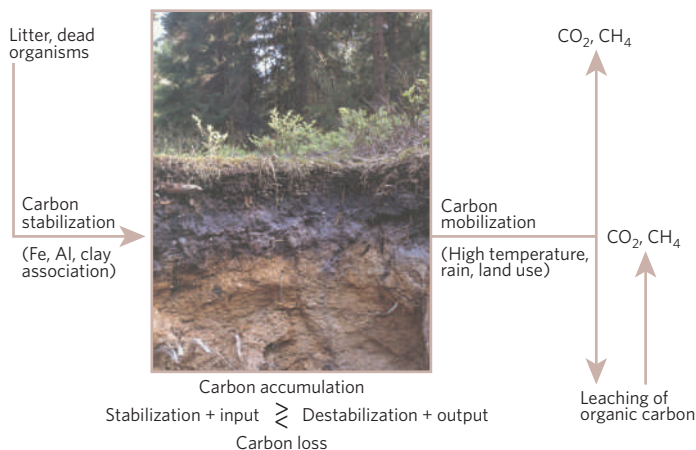
Soils are major players in the carbon cycle — globally, they store the equivalent of about 300 times the amount of carbon now released annually through the burning of fossil fuels. It is generally assumed that most of the carbon locked up in soils is inert, and stays there. But as Bellamy *et al.* report on page 245 of this issue¹, soil carbon may be more vulnerable to changing climate and patterns of land use than expected.

The carbon involved is known as soil organic carbon (SOC; Box 1). Bellamy *et al.* describe how they have determined the changes in SOC stocks in the top 15 cm of soils in England and Wales during the past 25 years. Their estimates are based on a soil inventory of almost 6,000 sites across all types of land use, resampled on a systematic grid from a

pre-existing larger inventory. They find SOC losses of an alarming magnitude. Extrapolating to the entire United Kingdom, Bellamy *et al.* estimate annual losses of 13 million tonnes of carbon. This is equivalent to 8% of the UK emissions of carbon dioxide in 1990, and is as much as the entire UK reduction in CO₂ emissions achieved between 1990 and 2002 (12.7 million tonnes of carbon per year).

These losses thus completely offset the past technological achievements in reducing CO₂ emissions, putting the United Kingdom's success in reducing greenhouse-gas emissions in a different light. Under the Kyoto Protocol, however, countries are not obliged to account for changes in the stock of soil carbon. So an effective climate policy will require a more comprehensive approach that includes all

Box 1 Soil carbon in context



Organic carbon is stored in the top layers of mineral soil as humus or above the mineral soil as peat or litter. This organic material is by no means in equilibrium — neither the carbon concentrations nor the depth of the soil layers are constant, although changes generally occur very slowly. Soils receive dead organic material, known as litter, mainly from the plant cover. This material is decomposed by the soil biota and partly mineralized, and is subsequently released to the atmosphere in the form of carbon dioxide and methane, or by leaching into groundwater¹³.

The subtle balance between input and output determines whether a soil is accumulating or losing carbon. Soil organic carbon (SOC) consists of diverse compounds with different chemical and physical properties; for scientific purposes, SOC is divided into an active and a passive pool, the latter being more resilient to further

degradation and possibly existing in soil for hundreds to thousands of years. All factors that reduce biological activity, and that stabilize SOC by physical protection or binding to clay silicates or metals, will promote accumulation; factors that increase biological activity and destabilization encourage degradation.

The interplay of these factors is highly complicated. For example, in humid regions, given an adequate supply of moisture, global warming may increase microbial activity and accelerate SOC mobilization; in drier areas, the converse may apply. Changing patterns of land use can also have significant effects. Losses of SOC occur when natural ecosystems are cultivated — because of degradation of soil fertility, intensified soil disturbance and reduced carbon input^{10,11}. If conservation measures are applied to degraded soils, however, the SOC content can be maintained or enhanced¹⁴.

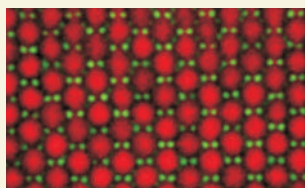
E.D.S. & A.F.

PHYSICAL CHEMISTRY

Isn't it ionic

Microscopic particles dispersed in solvents — known as colloidal suspensions — are attractive models for studying a wide range of phase transitions and nucleation phenomena. The suspended particles can be observed directly in three-dimensional space, and the interactions between them are easily modified. However, processes involving that seemingly most simple and ubiquitous of inorganic solids — ionic crystals formed from oppositely charged atoms — cannot be mimicked by colloids. Charged colloidal particles don't 'do ionic'; they prefer to aggregate instead.

But Mirjam E. Leunissen and colleagues, writing in this issue (*Nature* **437**, 235–240; 2005), show that colloids can be coaxed into forming ionic crystals after all. The authors observed that if salt is added to polymer spheres dispersed in an organic solvent mixture, the charge on the spheres can be controlled and the electrostatic interactions between them can be regulated. This enabled the preparation of binary mixtures of colloids that carried small, opposite charges and readily formed ionic crystals. When an electric field was applied, the crystal melted, and particles of



opposite charge moved towards opposite electrodes. The charged colloidal particles therefore clearly resemble ionic species. But there are differences. In particular, a diffuse layer of 'counter-ions' surrounds each particle, forming an overall charge-neutral unit that participates in the growth of the crystal. So the structure of the colloidal crystals is not dictated by charge neutrality, as in atomic systems, leaving the authors free to create remarkable

new binary structures. One example, a crystal comprising particles of positive (green, radius 0.36 μm) and negative (red, radius 1.16 μm) charge in the ratio 6:1, is shown in the image.

Colloidal crystals can also form from charged spheres made of different materials, such as a polymer and silica. It is then straightforward to burn the polymer spheres away to give all-silica structures. Given the ease with which these structures grow into large crystals, ionic colloids should prove an alluring proposition for those creating advanced materials such as photonic crystals.

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major carbon sources and sinks in the biosphere², with emphasis on protecting existing pools of stored carbon.

Bellamy and colleagues' observations are remarkable, and fall into four categories. First, consistent losses of SOC occurred independently of soil properties, challenging our knowledge about SOC stability. A new hypothesis suggests that the stability of SOC depends on the diversity and activity of soil microorganisms — if microbes have adequate energy resources, they can break down any organic structure irrespective of its physico-chemical stabilization³.

Second, the losses were proportional to carbon concentration, which implies a first-order decay of a homogeneous pool. This contradicts the view that SOC in carbon-rich soils contains a higher fraction of stable carbon than does that in carbon-poor soils. But it is unclear from which SOC fraction the lost carbon originated.

Third, SOC losses occurred in soils under all land-use conditions, and there is no apparent single factor other than climate change that could degrade non-agricultural soils. Fourth, the observation is contrary to the view⁴ that soils are an ultimate, large-scale sink for carbon.

The overall net loss of carbon identified by Bellamy *et al.* is unequivocal. But the authors can only speculate about where the carbon has gone. The reported changes in the top 15 cm correspond to average losses of 125 $\text{g C m}^{-2} \text{yr}^{-1}$, ranging from 66 $\text{g C m}^{-2} \text{yr}^{-1}$ uptake in extremely carbon-poor soils to 550 $\text{g C m}^{-2} \text{yr}^{-1}$ loss in carbon-rich (peat) soils. The SOC content may also have changed in soil layers not studied by Bellamy and colleagues. This may affect the magnitude of the overall carbon loss but is unlikely to negate the findings. Leaching of dissolved organic carbon cannot explain more than 10% of the loss^{5,6}, and it is likely that most of the rest has been converted to CO_2 .

Direct measurements of carbon flux do not yet provide a complete picture of the carbon cycle in ecosystems, and the 'mass balance' approach of Bellamy *et al.* is the only available evidence of change in the SOC pool. But the reasons for the loss remain unclear, irrespective of the pathways by which carbon is being lost. Re-inspecting the results, we think that the land-use factor has played a role — for example, only alteration in land use and gradual changes in land management can explain why croplands lost more carbon than other areas. Major land-use changes, such as the afforestation of carbon-rich soils, are not highlighted separately in Bellamy and colleagues' study.

Climate variation seems to be the second factor. Modelling studies suggest that significant changes in SOC stem from variations in precipitation and temperature on timescales of decades^{7,8}. But these conclusions are based only on laboratory studies and small-scale experiments. According to our current understanding of the sensitivity of soil respiration to warming, increased temperature alone seems to be too weak a driver. Carbon-rich soils lost most SOC. In the United Kingdom, these soils are often very wet and can easily be affected by changing precipitation patterns. The relative effects and combined impact of increased atmospheric CO_2 , warming, nitrogen deposition and altered precipitation are still disputed.

Bellamy and colleagues' observations are sure to stimulate further investigations to clarify the main uncertainties. International research projects such as CarboEurope, the Global Carbon Project and others⁹ are already under way with the aim of providing a better understanding of carbon balance in the biosphere. But this work is by no means straightforward. Soils are a nightmare to work with — they are dirty and highly varied in composition, and if a sample has been taken for analysis, that spot cannot be resampled.

The scientific and political implications

of the new findings¹ are considerable. The process of carbon loss from soils has been most comprehensively documented in the United Kingdom, both at regional level and under all forms of land use. But there have also been repeated warning signals from soil surveys in China¹⁰, Finland¹¹ and Flanders¹². These, however, attribute most of the SOC loss to changes in land use and management. In contrast, Bellamy *et al.* provide the first hint that regional climate variation may be contributing to a surprisingly large release of CO_2 from soils to the atmosphere. Further research into the carbon cycle and on reducing CO_2 emissions must take full account of areas where large pools of organic carbon are stored — or are being released. If we intend to stabilize the climate, such areas require much more serious consideration. ■

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- Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M. & Kirk, G. J. D. *Nature* **437**, 245–248 (2005).
- German Advisory Council on Global Change. *World in Transition: Towards Sustainable Energy Systems* (Earthscan, London, 2004).
- Gleixner, G. *et al.* in *Global Biogeochemical Cycles in the Climate System* (eds Schulze, E. D. *et al.*) 201–216 (Academic, San Diego, 2001).
- Schulze, E.-D. (ed.) *Carbon and Nitrogen Cycling in European Forest Ecosystems* (Springer, Berlin, 2000).
- Siemens, J. *Science* **302**, 1681 (2003).
- Worrall, F., Reed, M., Warburton, J. & Burt, T. *Sci. Total Environ.* **312**, 133–146 (2003).
- Tian, H. *et al.* *Tellus B* **51**, 414–452 (1999).
- Betts, R. A. *et al.* *Theor. Appl. Climatol.* **78**, 157 (2004).
- www.carboeurope.org; www.globalcarbonproject.org; http://daac.ornl.gov/FLUXNET; www.isse.ucar.edu/nacp/
- Wang, S. *et al.* *Tellus B* **55**, 416–427 (2003).
- Finnish Ministry of the Environment. *Finland's Third National Communication under the United Nations Framework Convention on Climate Change* (Environment Ministry, Helsinki, 2001).
- Sleutel, S. *et al.* *Glob. Change Biol.* **9**, 1193–1203 (2003).
- Schulze, E. D., Beck, E. & Müller-Hohenstein, K. *Plant Ecology* (Springer, Heidelberg, 2005).
- Follett, R. F. *Soil Tillage Res.* **61**, 77–92 (2001).