

however, use chemical gradients, light or other stimuli to passively or actively control the motion of the cell component.

The advantages of cellular 'motors' are that the overall system can be compact, fast and inexpensive; mass production of the microrobots would also be cost-effective if self-assembly processes were used. Furthermore, the cellular propulsion or actuation component could be multifunctional, perhaps serving as a biochemical sensor or navigation controller. Such systems are, however, limited by the often stochastic nature of cellular motion, and by the relatively brief lifetimes of cells (depending on the environments in which the robots are used).

Future challenges include finding methods for detecting, localizing and communicating with microrobots inside the body, and making and integrating on-board diagnostic and therapeutic tools. The safety of patients during operations must also be guaranteed: for example, it remains to be shown that microrobots can operate in the dynamic environments of the human body in a reliable, robust manner. And ideally, the instruments required for use in microrobots should be cheap and portable.

Moreover, methods must be found to program and control armies of microrobots, as this will be necessary if such devices are to treat large areas of the body, to increase the speed and success of medical operations, and to deliver sufficient amounts of drugs to their targets. Zhang and colleagues' method<sup>1</sup> of external actuation could in principle, be used to steer and coordinate such armies. But although this approach would certainly allow fast and effective control, it would also require complex instrumentation, robot design and fabrication. Alternatively, passive steering could be used to control large numbers of cyborg microrobots, for example by genetically engineering attached cells to be attracted towards a specific biochemical signal. This approach would be energy efficient and would not require bulky external equipment.

With so many engineering and medical challenges to be solved, clinically usable microrobots may not be viable for decades to come. Nevertheless, the demonstration of methods for making, powering and steering micro-metre-scale robots<sup>1,4-6</sup> are the first crucial steps towards such systems. ■

Metin Sitti is in the Department of Mechanical Engineering, Carnegie Mellon University, 320 Scaife Hall, Pittsburgh, Pennsylvania 15213-3890, USA.  
e-mail: sitti@cmu.edu

- Zhang, L. *et al. Appl. Phys. Lett.* **94**, 064107 (2009).
- Baudry, J. *et al. Nature* **437**, 862-865 (2005).
- Edd, J., Payen, S., Stoller, M. L., Rubinsky, B. & Sitti, M. *Proc. Int. Conf. Intelligent Robots and Systems* 2583-2588 (IEEE/RSJ, 2003).
- Darnton, N., Turner, L., Breuer, K. & Berg, H. C. *Biophys. J.* **86**, 1863-1870 (2004).
- Behkam, B. & Sitti, M. *Appl. Phys. Lett.* **93**, 223901 (2008).
- Weibel, D. B. *et al. Proc. Natl Acad. Sci. USA* **102**, 11963-11967 (2005).

## ECOLOGY

# Speciation affects ecosystems

Ole Seehausen

**Evidence that speciation and adaptive radiation can change the properties of an ecosystem is a reminder of the pressing need to integrate ecosystem science and evolutionary biology.**

Differences between ecosystems affect the rate and direction of evolutionary diversification. But does evolutionary diversification affect the functioning of ecosystems? On page 1167 of this issue, Harmon *et al.*<sup>1</sup> present experimental data from work with predatory stickleback fish that show that it does.

This insight comes at an opportune moment, as ecosystems ecology and evolutionary biology have existed separately for more than a century, and their integration is long overdue. Evolutionary biology is all about the dynamics that arise from interactions of genotypes with their environments and interactions among genotypes, which scale up to the dynamics of biodiversity in space and time. Ecosystems ecology, on the other hand, looks at dynamics predominantly in terms of fluxes of matter and energy, implicitly or explicitly assuming that these are unaffected by genotypic variation within species.

Building blocks for a synthesis have begun to emerge in several contexts, all emphasizing feedbacks between ecosystems and evolution<sup>2</sup>. Besides the well-established fact that environments change the course of evolution, evolution also changes the environment, and in turn, the environment changes evolution further, and so forth. The effects of a population on its environment are determined by its genotypic composition and evolutionary history; these effects change the form and strength of selection on the population itself ('niche construction') and of selection on other species ('ecosystems engineering'), and so determine the course of further evolution.

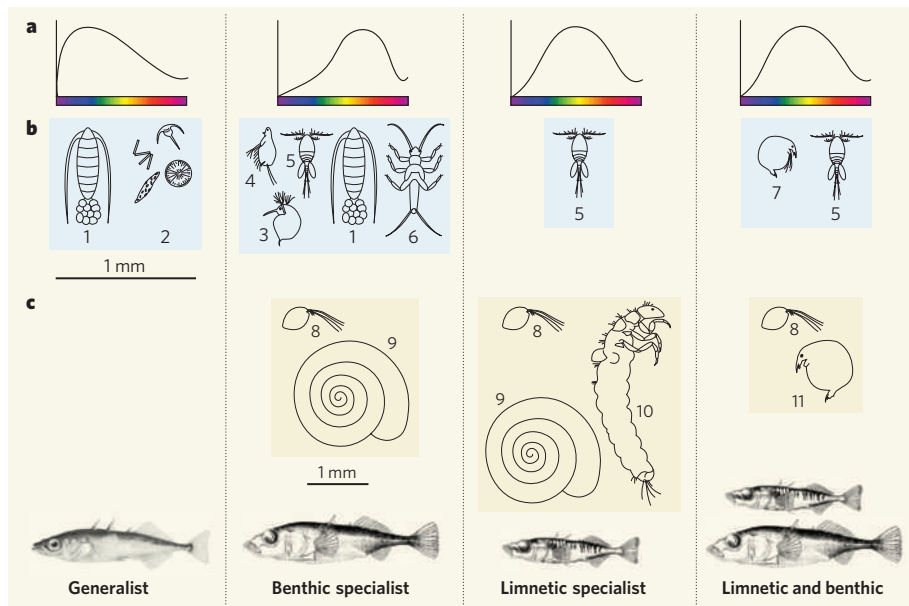
This feedback loop occurs on all timescales. Organisms produce effects on the environment that can persist over geological time and modulate macroevolution (that is, the origins of new taxonomic groups and biological assemblages)<sup>3</sup>. And evolution within a species — microevolution — can change ecosystem function. For instance, the evolution of predator life-history over the course of decades and centuries can have a profound impact on lower trophic levels, thereby driving changes in nutrient flux and primary production (algal growth)<sup>4</sup>, and influencing the further course of evolution in the predator itself<sup>5</sup>. Evolution of anti-predator defence can be so fast that it can even shape cyclical predator-prey dynamics, thought of as classical ecological dynamics<sup>6</sup>. But what has remained unknown is whether the splitting of one species into two affects ecosystem function.

This is where Harmon and colleagues<sup>1</sup> come in. They show that stickleback adaptive radiation — whereby one species splits into two or more, while adapting to alternative ecological resources<sup>7,8</sup> — has considerable effects on the composition and abundance of species at lower trophic levels. These consequences are then reflected in changes in the aquatic environment in terms of primary production, the composition of dissolved organic materials and light penetration — ecosystem features that in turn are likely to affect the course of adaptive radiation.

After the retreat of the glaciers at the end of the last ice age, marine threespine sticklebacks colonized fresh waters, and split into many nascent species adapted to different lifestyles and environments. In several lakes along the Pacific rim of British Columbia, Canada, two coexisting species evolved through 'ecological speciation'<sup>9</sup>, one adapted to life at the lake edge (the benthic species) and the other to life in the open water (the limnetic species). In other lakes, a single stickleback species is found. The solitary species tend to be ecological generalists, although their levels of specialization may vary between lakes.

Harmon *et al.*<sup>1</sup> used experimental mesocosms to address the question of whether it made a difference to ecosystem function that sticklebacks had specialized and speciated. They inoculated replicate mesocosms with the same assemblages of open-water and benthic invertebrate prey, but then included fish in four different ways: as a single generalist stickleback species; as each of two different specialized species; or as a sympatric (coexisting) pair of specialized species.

Relative to the unspecialized species, each specialized species on its own produced a reduction of primary production and an increase ('upregulation') of benthic invertebrates (Fig. 1). However, large benthic invertebrates were more strongly upregulated in the presence of a limnetic stickleback species, whereas small to large zooplankton (plankton consisting of tiny invertebrates) were upregulated in the presence of benthic sticklebacks. Even though these stickleback species were taken from the same lake, the implication is that adaptive differences between stickleback populations in different lakes may affect ecosystem structure and function. When both species of stickleback were present, only the smallest zooplankton and benthic invertebrates were upregulated. The implication here is that adaptive radiation within a lake changed



**Figure 1** Harmon and colleagues' experiments<sup>1</sup>. Initially identical ecosystems in mesocosms diverged depending on the recent evolutionary history of the experimental population of three stickleback predator species in four combinations — ecologically generalized; lake edge (benthic); open water (limnetic); and limnetic and benthic together. All of these sticklebacks share a common ancestor that existed no more than 10,000 years ago, and probably much more recently. The implication is that rapid speciation may cause rapid changes in ecosystem structure and function. **a**, Idealized light spectra resulting from each treatment. **b**, Open-water prey that became relatively abundant. **c**, Benthic prey that became relatively abundant. 1, *Skistodiaptomus* (copepod); 2, phytoplankton; 3, *Bosmina* (cladoceran); 4, *Diaphanosoma* (cladoceran); 5, *Cyclopoida* (copepod); 6, stonefly larva; 7, *Chydorus sphaericus* (cladoceran); 8, ostracod; 9, gastropod; 10, caddisfly larva; 11, benthic cladoceran. Note the different scales in **b** and **c**. (Fish images from refs 14, 15.)

its ecosystem from one dominated by phytoplankton (plankton consisting of microscopic plants) and large zooplankton to one dominated by small zooplankton and small benthic invertebrates. In mesocosms containing differently specialized species, or a species pair, the composition of dissolved organic material, and so the water's light-absorbance properties, also changed, altering the intensity and colour of light under water (Fig. 1a).

Intriguingly, the niche-construction effect of ecological speciation in predatory fish, through its effects on the light environment, may close a feedback loop to speciation. Variation in light exerts strong divergent selection between<sup>10</sup> and within<sup>11</sup> lakes, because it influences vision and mating preference and so may determine whether or not speciation happens<sup>12</sup>. Harmon *et al.* suggest that variation in the extent of niche construction between organisms might help to explain variation in the propensity to undergo adaptive radiation. If future research confirms this possibility, species diversity arising through adaptive radiation and ecosystem evolution would indeed seem to constitute a complete loop.

What next? Most obviously, there is a need to repeat the experiments with other, independently evolved pairs of stickleback species to see if the effects of adaptive radiation on an ecosystem are predictable. Then there is the question of whether such effects are indeed due to adaptive genetic divergence between

predator species, as Harmon *et al.* assume, or to non-genetic differences in behaviour or performance between sticklebacks collected from different habitats. Experiments with fish raised under identical laboratory conditions could be used to distinguish between these alternatives; eventually, this framework of research could be extended to adaptive radiations in which more

than two recently diverged species share the same ecosystem. Also, tests need to be devised to see if the effects seen in mesocosms apply in natural ecosystems. Altogether, these studies would permit the establishment of more general relationships between ecosystem functioning and adaptive radiation. As a by-product, such research will foster the synthesis of ecosystems science with evolutionary biology.

Implicit in this exciting news<sup>1</sup> is a warning relating to the rapid, human-induced collapse of species diversity in ecosystems dominated by recent adaptive radiations<sup>13</sup>. If the effects of adaptive radiation on the function of natural ecosystems are similar to those observed in the mesocosms, we should expect to see the collapse of nascent species diversity leading to severe perturbations in ecosystem functioning — a process that may in fact already be under way. ■

Ole Seehausen is at the Institute of Ecology and Evolution, University of Bern, and the Eawag Swiss Federal Institute of Aquatic Science and Technology, Center of Ecology, Evolution and Biogeochemistry, Seestrasse 79, CH-6047 Kastanienbaum, Switzerland. e-mail: ole.seehausen@eawag.ch

1. Harmon, L. J. *et al.* *Nature* **458**, 1167–1170 (2009).
2. Post, D. M. & Palkovacs, E. P. *Phil. Trans. R. Soc. Lond. B* **364**, 1629–1640 (2009).
3. Erwin, D. H. *Trends Ecol. Evol.* **23**, 304–310 (2008).
4. Palkovacs, E. P. *et al.* *Phil. Trans. R. Soc. Lond. B* **364**, 1617–1628 (2009).
5. Palkovacs, E. P. & Post, D. M. *Evol. Ecol. Res.* **10**, 699–720 (2008).
6. Yoshida, T. *et al.* *Nature* **424**, 303–306 (2003).
7. Schluter, D. *The Ecology of Adaptive Radiation* (Oxford Univ. Press, 2000).
8. Gavrillets, S. & Losos, J. B. *Science* **323**, 732–737 (2009).
9. Schluter, D. & McPhail, J. D. *Am. Nat.* **140**, 85–108 (1992).
10. Reimchen, T. E. *Evolution* **43**, 450–460 (1989).
11. Boughman, J. W. *Nature* **411**, 944–948 (2001).
12. Seehausen, O. *et al.* *Nature* **455**, 620–626 (2008).
13. Taylor, E. B. *et al.* *Mol. Ecol.* **15**, 343–355 (2006).
14. Kraft, C. E. *et al.* *Inland Fishes of New York (Online)* (Cornell Univ./NYSDEC, 2006).
15. McPhail, J. D. *Can. J. Zool.* **70**, 361–369 (1992).

## SOLID-STATE PHYSICS

# Lost magnetic moments

Richard Korytár and Nicolás Lorente

**A neat study gives clear-cut evidence that when a wire made of a magnetic material such as iron is squashed to the atomic scale, the material's magnetism disappears via an exotic physical process.**

Since the 1960s, it has been known that a magnetic impurity in a non-magnetic host metal is subject to a mechanism known as the Kondo effect. That is, below a characteristic temperature, the Kondo temperature, the metal's electrons screen the magnetic moment of the impurity<sup>1,2</sup>. In this context, ferromagnetic metals, such as those commonly used to make magnets for holding notes on refrigerator doors, are intriguing. These materials, which are marked out by their ability to

retain magnetization, can in principle screen a magnetic impurity<sup>3</sup>. But can a ferromagnet screen one of its own atoms? On page 1150 of this issue, Calvo *et al.*<sup>4</sup> show that this can be achieved when a ferromagnetic wire is reduced to atomic dimensions.

In their experiment, Calvo and colleagues created atomic-size ferromagnetic wires using two techniques known as scanning tunnelling microscopy and electromigration. These techniques allowed the authors to reduce the size