results in immune activation, growth of new blood vessels and modulation of tumour progression[10]. These neuroimmune interactions involve a mix of sensory, sympathetic and parasympathetic nerves that modify disease progression through direct interactions with affected tissue and the immune system.

Mohanta and colleagues' discovery that neuroimmune signalling also contributes to atherosclerosis is a valuable contribution to the field. The interactions that they have uncovered also feature a twist, in which atherosclerotic plaques remodel sympathetic and sensory nerves from a distance and through a barrier. The findings not only suggest new directions for research into possible treatments, but also raise the prospect that distant neural remodelling across barriers occurs in other organs and diseases – including those not generally thought to have a neural component.

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Food production

Environmental benefits of eating mycoprotein

Hanna L. Tuomisto

Would environmental damage be reduced by replacing beef with mycoprotein produced in cell culture? Modelling shows that this change could greatly cut global deforestation, pasture area and greenhouse-gas emissions. **See p.90**

The development of alternatives to animal-sourced foods has increased during the past few decades as a response to the negative environmental impacts of livestock production. These alternatives include foods that are produced by the industrial-scale culture of animal, plant and microbial cells. Studies have shown that, per unit of mass, cell-cultured foods can have a lower environmental footprint than that of proteins from livestock[1], but comparisons of global-level assessments have been lacking. On page 90, Humpenöder *et al.*[2] report the first global analysis of the environmental benefits that could be achieved by substituting beef with mycoprotein from cell culture.

Cell-cultured foods are produced by cultivating cells in bioreactors – usually, steel tanks – containing nutrients and other factors needed for cell growth. The cultivated cells can be used either directly as food or to synthesize substances (such as proteins or fatty acids) that make up food ingredients[3]. Most cell types source their carbon from glucose, which is generally obtained from agricultural crops, although some microbial cells can obtain carbon from methane or carbon dioxide[4]. Cropland is therefore required to produce feedstocks for most cell-cultured foods.

Humpenöder *et al.* investigated the environmental impacts of replacing beef with mycoprotein[5]. Many cell-cultured food products are still in development, but mycoprotein-based products are already widely available in supermarkets in many countries. Mycoprotein is an ideal substitute for meat because it is rich in protein and contains all the essential amino acids that humans obtain from nutrition. The products are textured and shaped to resemble common meat products, including processed foods (such as sausages and burger patties) and ingredients for cooking (such as minced beef or chicken breast).

The authors modelled the changes in land use, greenhouse-gas emissions, water use and nitrogen fixation (the biological process by which nitrogen gas is converted into compounds that can be used as nutrients by other organisms) that would result from replacing 20%, 50% and 80% of global beef consumption with mycoprotein. They used a 'middle of the road' socio-economic scenario as a baseline for estimates of the increases in population, income and livestock demand between 2020 and 2050. Their assessment of the environmental impact of mycoprotein culture considered the cultivation of sugar cane as a source of glucose, but ignored the effects of producing other nutrients and the energy required for the cell-culturing processes. In effect, the study therefore simply compared the land-use impacts of beef and sugar-cane production. The estimated quantity of sugar cane produced was based on the glucose requirements of culturing an amount of mycoprotein equivalent to that of the beef protein being replaced.

The modelling shows that the increase in beef consumption in the baseline scenario would require expansion of global pasture and cropland areas, causing a doubling of the annual deforestation rate between 2020 and 2050. Substituting 20% of beef consumption with mycoprotein halves the annual deforestation rate (Fig. 1). Over the same period, the scenarios assuming 50% and 80% substitution levels result in a decline in global pasture area and substantial reductions in annual deforestation rates.

The relationship between the percentage of beef substitution and the annual deforestation rates in 2050 is nonlinear. Because the pasture area required in 2050 at the two highest substitution levels is lower than that

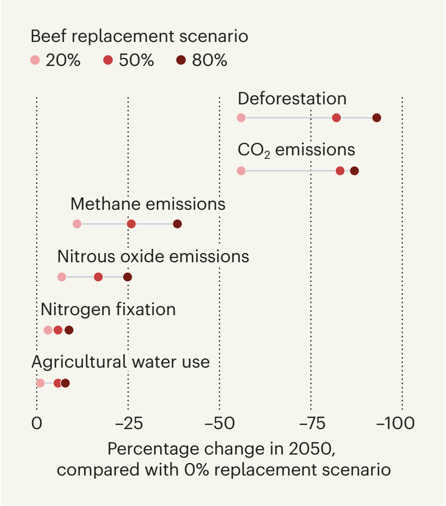

Figure 1 | Modelling the effects of switching from beef to mycoprotein consumption. Humpenöder *et al.*[2] estimated the global environmental impacts associated with replacing 20%, 50% and 80% of beef in people's diets with mycoprotein. In 2050, the substitutions have a large effect on deforestation and carbon dioxide emissions; a modest impact on emissions of methane (a greenhouse gas) and nitrous oxide (a gas pollutant associated with agriculture); and only a small effect on nitrogen fixation (the biological process by which nitrogen gas is converted into forms of nitrogen that can be used as nutrients by other organisms) and agricultural water use. (Adapted from Fig. 3g of ref. 2.)

in 2020, there is no need to clear forest for beef production in these scenarios, and some of the land that was once used for pasture can be converted to cropland. Moreover, in all of the substitution scenarios, the annual deforestation rates decline during the first 15–20 years and increase afterwards. This can be explained by structural changes in agriculture that occur over time, such as changes in agricultural yields and in the level of land degradation. Compared with the baseline scenario, all substitution levels resulted in large reductions in greenhouse-gas emissions from livestock production and land-use changes, but only minor changes in agricultural water use and nitrogen fixation.

Studies known as product-level assessments have previously estimated the environmental impacts of cell-cultured foods, per unit produced. Humpenöder and colleagues' study is a first step towards assessing how production affects specific types of land use and associated greenhouse-gas emissions over time. However, the study does not provide a complete picture of the environmental consequences of the transition from beef to cell-cultured foods. That's because its scope is limited to impacts associated with land use, and it does not consider all the ingredients and other resources needed for mycoprotein production.

Future research should expand the scope of the current study by considering the environmental impacts of other factors involved in food production. For example, product-level assessments have shown that producing cell-cultured food can require more electricity than does raising livestock[1]. The environmental impacts of energy generation therefore need to be considered, taking into account future capacity to expand sustainable electricity supplies. Glucose sources other than sugar cane should also be assessed; these could include crops such as sugar beet or grains that can be cultivated in boreal regions, as well as by-products from the production of other types of food or animal feed[6].

It should be noted that Humpenöder and colleagues' modelling is likely to overestimate the impacts of beef production and underestimate those of culturing mycoproteins. Beef production provides many by-products, such as milk, hides for leather production and fat for the chemical industry. If beef production were reduced, the by-products would need to be made in alternative ways, which would increase environmental impacts. Furthermore, large reductions in beef consumption would require a parallel reduction in the consumption of dairy products, at least in regions where most beef originates from dairy systems[7].

Further research into the environmental consequences of producing cell-cultured foods should include a wider range of products. These could include proteins produced by microorganisms that use CO_2 or methane as a carbon source[4]; milk and egg proteins produced by microbial cells[8]; and cultured meat made of animal cells[1]. The estimates of the environmental impacts would be improved by using scenarios that consider the availability and realistic adoption rates of cell-cultured foods in different socio-economic contexts. Global assessments will also be needed to find ways of making food systems more sustainable through innovative technologies combined with dietary changes, sustainable agricultural practices and reduced food waste.

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Neurobiology

Mental replays enable flexible navigation

Jérôme Epsztein

While rats pause to eat or rest during navigation tasks, neuronal sequences in the brain are replaying routes around moving obstacles, allowing the animals to reach their goals even in changing environments.

The ability to navigate is essential to daily life, whether someone is driving to work or walking to the coffee machine. To negotiate complex environments, one can follow instructions: 'turn right at the bakery', for example. This strategy is simple and requires little effort, but is inflexible – if the bakery is no longer there, one is lost. One could use a map instead: with external cues, one can locate oneself on the map and plot the shortest path to one's destination. This requires more effort but has the advantage that all routes (even unfamiliar ones) can be seen at a glance, allowing flexibility if, say, a street is blocked by traffic. Yet humans (and other animals) can also flexibly navigate complex and changing environments without instructions, and were able to do so well before the advent of maps (let alone GPS technology). How? Writing in *Neuron*, Widloski and Foster[1] report a role for replays of neuronal activity that represent spatial trajectories.

The hippocampus is a brain structure that is essential for flexible navigation in humans and many other animals, such as non-human primates, rodents and bats. Together with other structures in the temporal lobe, the hippocampus participates in the formation of a cognitive map – an internal representation of the external environment[2]. At the cellular level, the hippocampus is made up of neurons called place cells, the activity of which is modulated by someone's position in the environment. When the individual moves around, place cells are sequentially activated and indicate in real time the first piece of information needed for navigation: the current location[3].

This information is not, however, sufficient for navigation towards goals. The individual must also be able to locate those goals and evaluate the routes for getting there[4]. Is it possible for them to achieve this by mentally exploring their cognitive maps?

> **"These discoveries bring researchers one step closer to understanding the properties of our cognitive map."**

Research over the past 15 years has shown that sequences of place-cell activation that correspond to routes recently explored by an animal can be replayed about 20 times faster when animals are immobile (resting or eating, for example)[5] or asleep[6] than when they are moving. This replay occurs during short bouts of fast oscillating brain activity called ripples, and could represent high-speed mental travel through the cognitive map. Interestingly, these sequences feature trajectories in the forward order, but also backwards (akin