reduction of food-chain waste from field to plate. It is estimated that up to one-third of food doesn't reach the market (Fig. 1) or is discarded after purchase[9]. Reducing this waste would increase food availability without the need for extra food production.

Springmann and colleagues conclude that an intervention in only one of the three categories they analysed would not achieve planetary sustainability across all five of the environmental domains that they assessed. Instead, a bundle of interventions in all three categories would be needed to ensure that the global food system could be sustainably supported by the planet in 2050. They found that the projected greenhouse-gas emissions from agriculture would not be supportable unless global meat consumption was reduced. They also report that the expansion of cropland and water use would be best counteracted by improvements in agricultural technologies and management approaches that bring farming yields closer to the maximum yield efficiency that is ecologically possible. In addition, their analysis indicates that achieving fertilizer-use reduction would require a combination of measures that improve farming practices and decrease food demand.

There are some caveats regarding Springmann and colleagues' scenarios. For example, they did not take climate-change effects into account in their projections of future agricultural production, and such impacts should be a priority for future analysis. Also, the authors' analysis did not consider the world's grassland areas, even though they represent more than double the area of global cropland[10]. These grassland areas should be considered when setting planetary boundaries for land use. Moreover, Springmann and colleagues' study analyses only the environmental impacts of cropland-based food production — it doesn't assess how to balance these impacts with those in sectors such as energy, transport or industry.

Nevertheless, the authors' analysis is valuable and informative for the discussion about how to achieve a sustainable food system that meets future needs, even if some of the planetary-boundary values they used have large uncertainty ranges[11]. In addition, any proposed interventions should not be implemented using a one-size-fits-all approach. Instead, any regulatory frameworks and incentives will need to be tailored to the needs of a given region, whether this means investments in education, health-service access, land-use regulations or water allocation, for example.

Springmann and colleagues also did not address certain key issues that are needed to develop a resilient agricultural system. The rights of access to land and natural resources, and the long-term security of those rights, is needed to motivate investments by farmers. Farmers could also be helped by improvements in transport, finance and communication infrastructure that enable them to access advanced technologies, minimize their production risks and target their production for local or international markets.

A recent report[12] by the Food and Agriculture Organization of the United Nations concludes that environmental sustainability and food security can go hand in hand by 2050, but that substantial investments are needed to transform the global food system. Political and public commitment will be essential to ensure increases in budgets for the development of international agriculture.

Food demand and food production are two sides of the global food-system equation. Springmann and colleagues' work provides a timely warning that interventions will be needed in both domains to achieve food security in the future, and to ensure that the environmental impacts of the food-production system remain within boundaries that Earth can sustain. ■

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MATERIALS SCIENCE

The war on fake graphene

The material graphene has a vast number of potential applications — but a survey of commercially available graphene samples reveals that research could be undermined by the poor quality of the available material.

PETER BØGGILD

Graphite is composed of layers of carbon atoms just a single atom in thickness, known as graphene sheets, to which it owes many of its remarkable properties. When the thickness of graphite flakes is reduced to just a few graphene layers, some of the material's technologically most important characteristics are greatly enhanced — such as the total surface area per gram, and the mechanical flexibility of the individual flakes. In other words, graphene is more than just thin graphite. Unfortunately, it seems that many graphene producers either do not know or do not care about this. Writing in *Advanced Materials*, Kauling *et al.*[1] report a systematic study of graphene from 60 producers, and find that many highly priced graphene products consist mostly of graphite powder.

Imagine a world in which antibiotics could be sold by anybody, and were not subject to quality standards and regulations. Many people would be afraid to use them because of the potential side effects, or because they had no faith that they would work, with potentially fatal consequences. For emerging nanomaterials such as graphene, a lack of standards is creating a situation that, although not deadly, is similarly unacceptable.

One of the most well-established methods for producing graphene for commercial applications is liquid-phase exfoliation[2] (LPE) — a process that involves milling graphite into a powder, and separating the particles into tiny flakes by applying mechanical forces in a liquid. Those precious flakes that contain just a few layers of graphene are then separated from the rest (Fig. 1). Graphene produced in this way has a huge number of potential applications, including battery technology, composite materials and solar cells. The LPE of graphite was first achieved using sonication to produce the flakes[3], and later work showed that even a kitchen blender[4] can be used to create violent turbulent forces that pull graphene sheets apart without destroying them.

But how thin must graphite flakes be to behave as graphene? A common idea, backed up[5] by the International Organization for Standardization (ISO), is that flakes containing more than ten graphene layers are basically graphite. This seemingly arbitrary threshold has some basis in physics, as Kauling *et al.* note. For example, thermodynamic considerations dictate that each layer of atoms in a flake of ten or fewer layers behaves as an individual graphene crystal at room temperature.

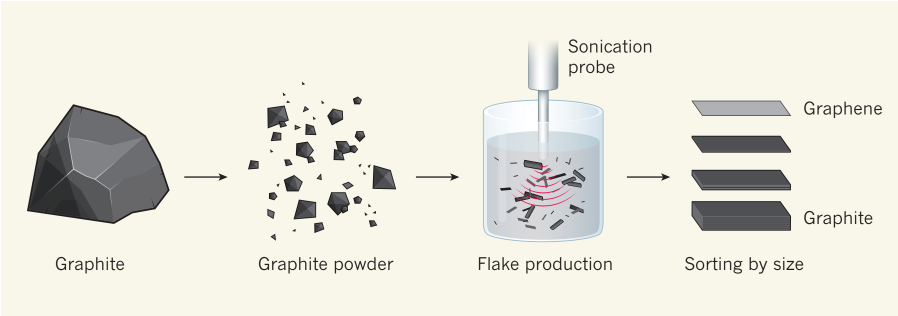

Figure 1 | Liquid-phase exfoliation of graphene. Most commercially available bulk graphene is made by milling graphite into powder, and then subjecting the resulting particles to mechanical forces in a liquid solution to separate the powder into flakes, for example, by using sonication; flakes not shown to scale. The flakes are then sorted according to their size and thickness. Kauling *et al.*[1] analysed commercially available graphene from 60 providers, and found that the majority of the samples contained less than 10% of graphene (flakes that contain fewer than ten layers of carbon atoms[5]). The rest is essentially just graphite powder. (Adapted from ref. 1.)

Moreover, the rigidity of flakes scales with the cube of layer thickness, which means that thin graphene flakes are orders of magnitude more flexible than thicker graphite flakes.

So size really matters: depending on the practical application, graphene and graphite powders can give entirely different results. Without clear standards by which to determine the quality of commercially available graphene, companies and researchers risk wasting time and money doing research on graphite powder disguised as expensive, high-grade graphene. This would stunt the development of graphene technology, harming serious graphene producers and application developers alike.

But are these concerns truly warranted? In a study aimed at answering this question, Kauling *et al.* established a systematic test protocol based on an arsenal of well-established methods for characterizing graphene, and then used the protocol to benchmark 60 graphene products from different producers, a daunting task. The results showed that the statistical distributions of the key material indicators — such as the size, structural integrity and purity of the graphene — varied greatly. Shockingly, the study revealed that less than 10% of the material in most of the products consisted of graphene composed of ten or fewer layers. None of the products tested contained more than 50% of such graphene, and many were heavily contaminated, most likely with chemicals used in the production process.

It seems that the high-profile scientific discoveries, technical breakthroughs and heavy investment in graphene have created a Wild West for business opportunists: the study shows that some producers are labelling black powders that mostly contain cheap graphite as graphene, and selling them for top dollar. The problem is exacerbated because the entry barrier to becoming a graphene provider is exceptionally low — anyone can buy bulk graphite, grind it to powder and make a website to sell it on.

Unless common standards and test protocols are introduced, there is a great risk of dropping the ball at the worst possible time. Dozens of emerging applications for graphene are closely linked to some of society's grand challenges: health, climate, renewable energy and sustainability. Some of these applications might never leave the starting block if the early development is based on 'fake graphene'.

Kauling and colleagues' article is therefore a much-needed wake-up call for graphene producers, buyers and researchers to agree on and to adhere to sound standards: a transparent graphene market would benefit everyone, except perhaps unscrupulous vendors. The first steps towards this have already been taken with the ISO's graphene vocabulary[5] (a document that defines standard terminology for describing graphene) and the UK National Physical Laboratory's helpful Good Practice Guide for graphene characterization[6]. Now it's time to push on.

It should be noted that Kauling and co-workers' study does not cover all the types of bulk graphene on the market[7]. Moreover, although the authors analysed an impressive number of LPE-manufactured products, they could have eliminated any accusations of potential bias by specifying the criteria they used to select the products for analysis. It is also possible that they unintentionally missed high-quality graphene sold by a few excellent producers. And, as the researchers mention, different applications generally make use of different characteristics of graphene — which makes it difficult to come up with a universal metric of quality.

Nevertheless, the work is a timely and ambitious example of the rigorous mindset needed to make rapid progress, not just in graphene research, but in work on any nanomaterial entering the market. To put it bluntly, there can be no quality without quality control. ■

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NEUROSCIENCE

Senescence mediates neurodegeneration

Aggregation of the protein tau is implicated in neurodegenerative diseases in humans. It emerges that eliminating a type of damaged cell that no longer divides can prevent tau-mediated neurodegeneration in mice. SEE LETTER P.578

JAY PENNEY & LI-HUEI TSAI

There is strong interest in understanding how neurodegeneration is affected by a cellular state called senescence, in which cells stop dividing, suppress intrinsic cell-death pathways and release pro-inflammatory molecules that can harm healthy neighbours[1,2]. On page 578, Bussian *et al.*[3] examine the role of senescent cells in a mouse model of a type of neurodegeneration that involves aggregation of the protein tau. They find that neuronal expression of mutant tau triggers senescence in glia, the support cells of the brain. Preventing the build-up of senescent glia can block the cognitive decline and neurodegeneration normally experienced by these mice.

Senescent cells are characterized by various molecular and gene-expression changes, including elevated levels of the cell-cycle inhibitor protein $p16^{INK4A}$. Senescence can be identified by a test that stains cells blue if they