and ferroelectric properties in WTe_2. The ferroelectricity results from the transfer of charge between separate layers, whereas the metallic behaviour arises from electron conduction within each layer. The electrical polarization is, therefore, not affected by the presence of conduction electrons that are confined to the layers. And because the metallic and ferroelectric properties of WTe_2 are coupled, the electrical resistance abruptly changes when the polarization is switched.

The type of $MoTe_2$ studied by Jindal *et al.* has the same crystal structure as the WTe_2 reported in 2018 and, as is often the case, substitution of one type of atom (W) with another (Mo) in the same group in the periodic table results in a material with similar properties. In this case, the $MoTe_2$ also exhibits superconductivity when cooled to 0.1 kelvin (ref. 4). Members of the same research group as Jindal and colleagues reported that this transition temperature shifts up to 7 K when $MoTe_2$ is prepared as a single layer of atoms, and up to 2 K when it exists as bilayers[5]. Together, these findings suggest that ultrathin $MoTe_2$ should exhibit coexisting ferroelectricity and superconductivity.

The authors showed that this is indeed the case by fabricating a device made from bilayer $MoTe_2$, in which the charge-carrier density and external electric field can be independently tuned. When they applied the field, the resistance of the sample switched in a manner indicative of ferroelectric polarization switching. They simultaneously confirmed that the transition to a superconducting state occurred at around 2 K, making the material a ferroelectric superconductor.

Jindal *et al.* then studied the resistance at low temperatures to investigate the interaction between ferroelectricity and superconductivity. Surprisingly, these properties are tightly coupled. When the polarization is switched by the external electric field, the material suddenly turns from a superconductor with zero resistance into a normal metal with non-zero resistance. Because of the way that the polarization changes, the switching is non-volatile: the $MoTe_2$ transforms from a superconductor into a normal metal on application of an electric field pulse, and stays in this state indefinitely until the next pulse is applied.

The authors then went one step further to investigate the nature of the superconductivity. The temperature at which a material transitions to superconductivity depends on its charge-carrier density, and the authors showed that this superconducting temperature reaches a maximum in $MoTe_2$ at the point at which charge carriers that are negative (electrons) and positive (holes) coexist and have almost equal densities. This indicates that the superconductivity in this material has an unconventional origin, meaning that it doesn't conform to the standard theories of superconductivity. Further theoretical and experimental studies are required to reveal the origin of superconductivity, as well as the microscopic mechanism behind the coupling between superconductivity and ferroelectricity.

The existence of a ferroelectric superconductor was previously considered impossible, so Jindal and colleagues' discovery will certainly stimulate future investigations of the physics of $MoTe_2$, as well as its possible applications. For example, the material could be used to build reconfigurable superconducting devices that can switch between a magnetic sensor, a photon detector and a superconducting quantum bit (qubit) in a single substance. And because the authors' material is a layered structure, it is also possible to take advantage of advances in the assembly of van der Waals materials[6].

Are there any other ferroelectric superconductors[7]? It might be possible to find them by applying the concept of artificial ferroelectricity, in which non-ferroelectric van der Waals materials can be made to be ferroelectric by changing the stacking order[8–10]. Scientists working on stacked ultrathin materials have also come to realize that the extraordinary properties of these substances are even more exotic when the layers are twisted relative to each other[11]. It will be intriguing to learn how the ferroelectricity and superconductivity of $MoTe_2$ (and the coupling between them) are affected by twisting its layers, or by stacking $MoTe_2$ with other materials[12]. Such pursuits are just the starting point for the new line of superconductor and ferroelectrics research opened up by Jindal and colleagues' discovery.

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Biogeochemistry

How to feed the world with less nitrogen pollution

Longlong Xia & Xiaoyuan Yan

An analysis of more than 1,500 field observations has identified a collection of agricultural practices that can improve the use of nitrogen fertilizers – boosting crop yields while reducing environmental pollution. **See p.77**

Two of the greatest challenges that face society are finding a way to feed the world's growing population and preventing environmental pollution[1,2]. Nitrogen fertilizers are needed to produce enough food for the planet's 8 billion people, but it's possible to have too much of a good thing – overuse of these fertilizers results in substantial quantities of nitrogen being released into the environment, polluting the air and water. On page 77, Gu *et al.*[3] investigate this apparent conflict in nitrogen-fertilizer use, and find that the adoption of advanced nitrogen-management practices could allow more food to be produced than is produced today, but with less nitrogen pollution. Moreover, the societal benefits of mitigating nitrogen pollution from agriculture far exceed the costs associated with implementing these practices.

Globally, only around 40% of the nitrogen fertilizers applied to agricultural land is taken up by crops (the nitrogen use efficiency, NUE, is 40%)[4]. By contrast, about half is lost to the environment through the gaseous emission of nitrogen compounds and the leaching and runoff of dissolved nitrogen compounds to water bodies[4,5], reducing air and water quality and damaging human health. To make matters worse, the use of nitrogen fertilizers has increased continuously during the past few decades, yet the yields of staple crops in 24–39% of the world's agricultural land have not risen accordingly[6]. This indicates that environmental nitrogen pollution associated with fertilizer use is increasing. Agronomists are therefore endeavouring to find a 'win–win' strategy to produce more crops with less nitrogen pollution.

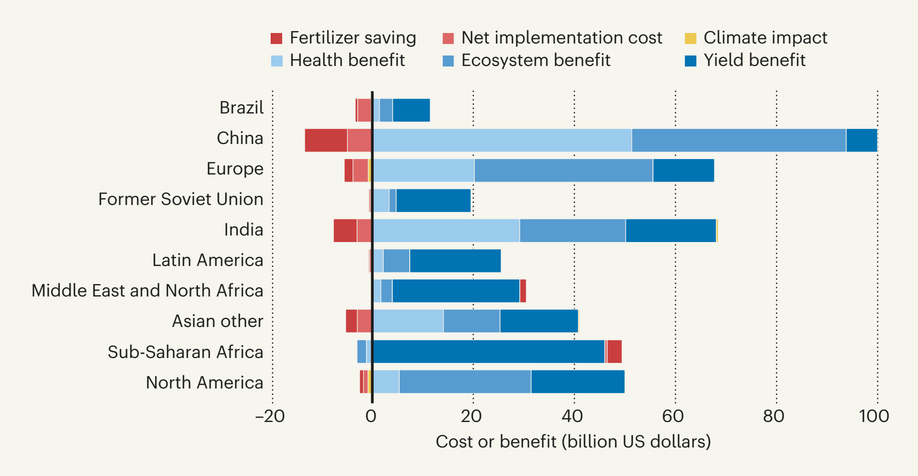

Figure 1 | Costs and benefits of a selection of nitrogen-management practices. Gu *et al.*[3] identified 11 advanced practices that enhance crop yield and the efficiency of nitrogen-fertilizer use, while decreasing pollution resulting from the release of nitrogen from fertilizers to the environment. They then used computational modelling to analyse the financial costs and benefits that would result from optimal global implementation of these practices – considering not only crop yields and fertilizer savings, but also the outcomes of advanced nitrogen management for climate, ecosystems and human health. The results are shown here for several of the main regions of the world, taking nitrogen-fertilizer use in 2015 as the baseline scenario for comparison. Negative values are costs, positive values are benefits. Implementation costs are net costs for farmers to adopt the practices, accounting for fertilizer savings. (Adapted from Fig. 3a of ref. 3.)

To address this challenge, Gu *et al.* conducted a meta-analysis of 1,521 field observations of advanced nitrogen-management practices published during the past two decades, analysing the effects of these practices on crop production and nitrogen losses. The authors identified 11 key practices that enhance crop yield and fertilizer NUE while decreasing nitrogen losses to the environment. Practices that synchronize crop nitrogen demand with supply[7,8] – known as '4R nutrient stewardship' (right fertilizer type, amount, placement and time) – are particularly effective in reducing nitrogen pollution.

Using computational modelling to extrapolate the effects of rolling out the 11 management practices globally, and taking conventional nitrogen-fertilizer use in 2015 as a baseline scenario for comparison, the authors identified multiple benefits. For example, crop nitrogen uptake was boosted by 20% compared with uptake levels in 2015, pollution to the environment was reduced by 32% and global use of nitrogen fertilizers fell by 21%.

However, advanced nitrogen management usually comes at a price. Farmers need to invest money, time and labour before they can fully apply such practices to their own land, and these implementation costs have become the largest barrier to the widespread adoption of nitrogen management in many countries[7]. On the basis of a cost–benefit analysis, Gu and colleagues conclude that the global societal benefits of reducing agricultural nitrogen pollution are more than 15 times the implementation costs – taking into account the enhanced crop yields, reduced premature mortality from respiratory diseases caused by air pollution, and the sustained services provided by unpolluted ecosystems (Fig. 1).

Nevertheless, it is a great challenge to change farmers' nitrogen-management practices, especially those of smallholders who often work part-time in non-agricultural sectors (the income from which can easily exceed that from agriculture[9]). Strong policy interventions are therefore needed to provide an incentive for farmers to adopt advanced nitrogen-management systems. The 'nitrogen credit system' proposed by Gu and colleagues is a timely attempt to address this issue. The idea is that societies that benefit from the mitigation of nitrogen pollution and increased food supply provide funds to subsidize farmers who adopt advanced nitrogen management.

The key to implementing a nitrogen credit system is securing the financial budget. The funds could come from taxing food consumers or enterprises that use farming for the commercial production of food, or by taxing agricultural polluting activities or products. For low-income countries in sub-Saharan Africa, where food shortages are due to an insufficient supply of nitrogen fertilizers rather than agricultural nitrogen pollution, money should also come from voluntary donations from local industrial enterprises and other stakeholders. Governments should mandate a nitrogen credit board to supervise the collection of funds and to transfer subsidies to farmers. They should also have the ability to apply sanctions to farmers who have received funds when their nitrogen management is inadequate[9].

The road to better nitrogen management through policy intervention is a thorny one, but is still promising. For example, the overuse and mismanagement of nitrogen fertilizers in China resulted in much lower NUE than the global average, and in nitrogen pollution[4]. To change this situation, the Chinese government invested about US$1.2 billion between 2005 and 2015 to implement a national nitrogen-management programme called 'testing and formulated fertilization'[10]. Through the efforts of participating governments, agricultural departments, research institutes and farmers, the nation's NUE for crop production increased from 35% to 42% (refs 11, 12). The launch of a follow-up programme, 'zero-increase action plan for fertilizer use', in 2015 is likely to result in a continuous rise in the NUE of crop production in China[11].

Future research should focus on determining the best nitrogen-management practices for different regions by considering local socio-economic factors (such as the availability and costs of labour, and the knowledge level of farmers), regional climate and soil conditions, as well as crop-variety differences. All of these factors can greatly influence the effects of advanced nitrogen-management practices on crop production and nitrogen losses to the environment. Moreover, as Gu and colleagues show, field studies exploring the impact of nitrogen-management practices are overwhelmingly focused in countries of the Northern Hemisphere. More studies are therefore needed in the global south, particularly in sub-Saharan Africa and South America, to get a better view of the effectiveness of these practices around the world. With the global population predicted to reach 9.7 billion in 2050, better use of nitrogen fertilizers is the only way to feed the world while reducing nitrogen pollution.

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