Energy decarbonisation threatens food security by reducing the availability of cheap sulfur

Simon Day[1]*, Peter Alexander*[2,3]*, Mark Maslin*[4]

The overlooked link between fossil fuel-derived sulfur and the production of phosphate fertilizers may lower agricultural productivity and harm global food security unless action is taken.

Application of fertilisers containing nitrogen (N), phosphorous (P) and potassium (K) have underpinned the dramatic increases in food production (gross production increased 3.7-fold between 1961 and 2020[1]), predominately from improving yields with intensive agricultural systems[2]. However, the decarbonisation of the energy sector will reduce the availability of cheap sulfur, which could jeopardise fertiliser supply and have major implications for food security. Here we discuss the risks of this overlooked link and approaches to mitigate them.

Sulfur's hidden role in fertilizer production

Two inputs are critical to the manufacture of phosphate fertilizer: mined phosphate rock and sulfur. Existing studies of the future security of phosphate fertilizer supplies have focussed on the large reserves of phosphate rock, which may represent up to 300 years or more of mining at present rates[3]. Previous concerns about the phosphate rock supply have been largely rejected in recent years[3,4]. In contrast, little consideration has been given to the sources of the required sulfur. Concentrated sulfuric acid is used to make the inert phosphate minerals in the mined rock bioavailable, as compounds such as calcium hydrogen phosphate, phosphoric acid and its salts (e.g., ammonium phosphate) that are used as P fertilizers. However, the acid is expensive to store safely and represents a potentially lethal hazard in case of release, so most users produce it continuously directly from elemental sulfur (Figure 1). The majority (60%) of global sulfur production is used to make fertilizers including phosphates, ammonium and potassium sulfates[5]. Phosphoric acid production alone accounts for over 45% of sulfur demand. This sulfur is currently almost entirely (99% of the 68 Mt of sulfur[5]) separated from crude oil and natural gas as part of the refining processes (Figure 1). Phosphate fertilizer production is therefore dependent upon the oil and gas sector to supply large quantities of cheap sulfur feedstock.

The fossil fuel industry desulfurizes its products for two reasons: first, to enable use of platinum, rhenium and other noble metal catalysts in refining streams that generate high-value products such as automotive petrol (gasoline), and jet fuel; and, second, to be compliant with post-1980s rules limiting sulfur content in all refined fuel products (due to the acid rain problem[6]). This produces an abundance of sulfur, since sulfur compounds typically form a few percent of crude oil and natural gas, and up to 15-23% in the case of particularly sulfur-rich "sour" hydrocarbon fields. Storage of sulfur is problematic, as stockpiles can catch fire creating severe SO_2 pollution events[7], creating additional incentives to find uses for the sulfur. The result is generally a low price for sulfur to industries who use it as feedstock in their processes, and in the process provide a hazardous waste disposal service to the oil and gas refiners. In inflation-adjusted terms, sulfur prices over the first decades of the 21st Century have been generally less than 20% of the prices paid before the 1980s when the sulfur emissions reduction legislation began to bite. However, because sulfur is derived from the oil and gas industry, market prices for sulfur can be extremely volatile. When there is a drop in oil and gas production and a shortfall develops the sulfur price can increases rapidly. For example, in the post-2008 financial crash recession, sulfur prices went from around \$20/ton to around \$200/ton[8].

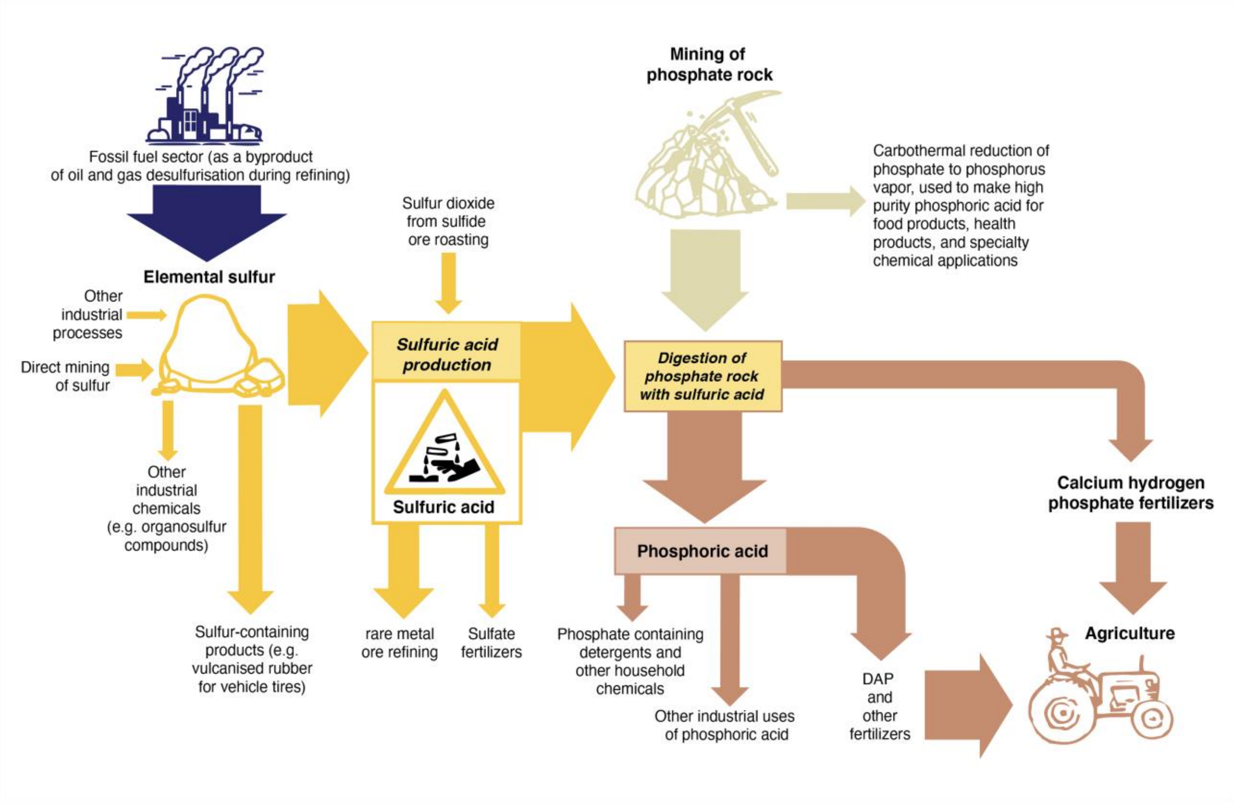

Figure 1: Material flows related to production and use of phosphate fertilisers. *The diagram shows the links between sulfur by-product from the fossil fuel sector, through sulfuric acid use in processing phosphate rock, and finally to the use in agriculture.*

Future trends in sulfur supply and market prices

A key implication of the relationship between oil and gas refining on the one hand, and sulfur users on the other, is that reductions in future fossil fuel use would reduce supply of sulfur from the sector and therefore limit phosphate fertilizer production as well as increase costs. Achieving higher climate mitigation objectives, such as net zero by 2050 necessary to limit warming to 1.5°C[9], will require an energy sector is based on renewable rather than fossil fuel energy[10]. Achieving this objective implies very large reductions in oil and gas production and use, meaning less sulfur by-product would be available from that industry under such a scenario.

More than 246 million tonnes of sulfuric acid are used annually at present, most of which in phosphate fertilizer production. Without constraints on sulfur availability, this could be expected to rise to over 400 million tonnes by 2040[8]. Depending on how quickly global decarbonization occurs, there could be a shortfall in the annual supply of sulfuric acid of

100-320 million tonnes by 2040[8]. Furthermore, sulfur demand for other uses will continue to increase, particularly because inputs of sulfuric acid are required in the production of critical metals for batteries and other technologies, upon which the transformation to post-fossil-fuel economies will depend. Since their products are aimed at affluent purchasers, these renewable technologies are likely to be able to outbid fertilizer producers as the price of sulfur rises, and so there may also be an additional decrease in the proportion of this declining supply of fossil fuel sulfur that goes to the phosphate fertilizer industry.

Unanticipated or sudden events (i.e., shocks) have impact on these markets on a shorter time scale. For example, the Russian invasion of Ukraine has impacted fertiliser markets with implication for food security[11]. Russia provided 6% of global phosphate rock production in 2021[4]. However, further impact on fertilizers may result from the disruption of oil and gas production, and hence to sulfur production. In 2021, sulfur production, almost all as a by-product of oil and gas industries, in Russia and Kazakhstan (whose oil and gas production depends largely upon export routes through Russia) represented 9.4% and 5.6% of global sulfur production, respectively[12]. Furthermore, if oil and gas production falls worldwide because of fuel price increases and economic recession, imbalances in the supply and demand for sulfur may cause sulfur price instability similar to that which occurred after the 2008 financial crisis[8]. Current global fossil fuel production has not yet been substantially impacted[13], but longer-term many countries and regions are accelerating the shift to renewable energy because of the conflict.

Phosphate fertilizers' links to food security

Phosphorous is essential for plant growth. If plant-available P in soil drops below critical species-specific levels, crop yields decline by about a factor of two[14]. Syers et al.[14] define four pools of varying plant availability, ranging from immediately available P dissolved in the soil water, to very low availability P in soil mineral grains and precipitates. In this framework, the purpose of phosphate rock processing with sulfuric acid can be stated as the conversion of very low availability phosphate rock grains into water soluble fertilizers that increase the concentration of immediately available P in the soil water. In that past 60 years, P fertiliser use has increased by 450%[15] and contributed to more than tripling of cereal yields[16]. Farmers in higher-income countries and China and India have, in recent decades, built up reserves of residual P in cropland soil[3], although not all are immediately available for plant uptake; in contrast, most African and some South American countries have mainly P-deficient soils to which little P fertilizer has been added in recent decades[17], and are more immediately vulnerable to reduced availability of P fertilizers.

Achieving increasing crop yields has been key to reducing global food insecurity. However, the global food system is currently facing pressures from a changing climate, geopolitical events (and the associate energy price shock), and greater competition for land, e.g., from need to use land for biodiversity conservation and for climate change mitigation actions. These pressures make maintaining or increasing per-area agricultural yields critical for provision of global food supplies. If P fertiliser production is impacted through the decarbonisation of the energy sector, reductions in agricultural yields (due to constraints on P fertiliser availability) or higher agricultural input costs (from increases in P fertiliser prices) would both contribute to food price increases. While buffering of P in the soil may give some additional time, i.e., over several years[14], to adapt in areas of previous high fertilizer applications, the speed and spatial variability of yield responses to alterations in P fertiliser use is uncertain due to a lack of research, particularly for soil in lower income countries where previous applications of P fertilizers have been minimal. These are also the countries where higher food prices would create the greatest harm, with serious consequences for malnourishment and associated mortality[11].

Options to avoiding the trap

One possibility to avoid the problem of decreased sulfur availability is to apply unprocessed phosphate rock powder, but the low availability P would be very inefficient and cause potentially severe environmental risks through eutrophication of rivers, lakes, and coastal areas. Another possibility is to find alternative sources of sulfur, for example from mining, which could be used in the P fertiliser production process. On decadal timescales, there is a variety of potential technology-change and demand reduction solutions that are technically feasible, although associated with increased costs. Perhaps the most sensible approach would be to promote circular food systems and increase recycling of both sulfur and of phosphorus[3] (from fertilizer to sewage to fertilizer e.g., via struvite precipitation at wastewater treatment plants), which can only occur in countries with a functional system of sewage collection and treatment.

Farming practices could be adapted to increase P use efficiency or increase the plants access P within the soil, e.g., in mineralised pools. Plant breeding could be used to selected for improving the efficiency of P use, e.g., through root hair length and organic acid production. Bio-fertilisers include inoculants containing fungi, rhizobacteria or P-solubilising microorganisms could be used[14]. These require time to develop, including variations based on different soil, crop, and climatic conditions, as well as time lags in adoption of the practices by farmers. The long-term soil P balance need to be maintained, with withdrawals from crop harvest balanced by inputs, however there is potentially for this P to be applied in mineralised form and therefore avoiding the dependency on sulfur and by association the fossil fuel sector. Changes in food demands to a more plant-based diet also reduce the amount of land required for farming and reduce the need for fertilizers.

Interdependencies between fossil fuels, sulfur and fertilizers need to be recognised. Careful planning will be required as the energy sector decarbonises to avoid increasing global food insecurity, with greatest implications for the poorest in society. Regulatory, technology and economic solutions will all be required.

References

1. FAOSTAT. *Production Indices*. https://www.fao.org/faostat/en/#data/QI (2023).
2. Alexander, P. *et al.* Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. *Glob. Environ. Chang.* **35**, 138–147 (2015).
3. Brownlie, W., Sutton, M. A., Heal, K. V., Reay, D. S. & Spears, B. M. *Our Phosphorus Future*. (2022). doi:10.13140/RG.2.2.17834.08645.
4. U.S. Geological Survey. *Phosphate rock*. *Mineral Commodity Summaries: Phosphate Rock* https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-phosphate.pdf (2023).

5. S&P Global. Commodity Insights: Sulphur Fertilizer Market and Price Analysis. https://www.spglobal.com/commodityinsights/en/ci/products/fertilizers-sulphur.html (2022).
6. Grennfelt, P. *et al.* Acid rain and air pollution: 50 years of progress in environmental science and policy. *Ambio* **49**, 849–864 (2020).
7. Potenza, A. This blue sulfur hellfire in Wyoming is mesmerizing — and toxic. *The Verge* (2017).
8. Maslin, M., Van Heerde, L. & Day, S. Sulfur: A potential resource crisis that could stifle green technology and threaten food security as the world decarbonises. *Geogr. J.* **188**, 498–505 (2022).
9. Shukla, P. R. *et al. Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. *IPCC* (2022).
10. IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. *Int. Energy Agency* 224 (2021).
11. Alexander, P. *et al.* High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. *Nat. Food* (2022) doi:10.1038/s43016-022-00659-9.
12. USGS. *Mineral Commodity Summaries 2022*. (2022) doi:10.3133/mcs2022.
13. IEA. *Oil Market Report: Data, forecasts and analysis on the global oil market*. https://www.iea.org/topics/oil-market-report (2023).
14. Syers, J. K., Johnston, A. . & Curtin, D. *Efficiency of soil and fertilizer phosphorus use*. *Food and Agriculture Organization of the United Nations* vol. 9 (2008).
15. Ritchie, H., Roser, M. & Rosado, P. Fertilizers. *Our World In Data* https://ourworldindata.org/fertilizers (2023).
16. FAOSTAT. *Crops and livestock products*. https://www.fao.org/faostat/en/#data/QCL (2023).
17. Alewell, C. *et al.* Global phosphorus shortage will be aggravated by soil erosion. *Nat. Commun.* **11**, (2020).

Author information

Affiliations

1 Institute for Risk and Disaster, UCL, Gower Street, London, WC1E 6BT, UK.
2 School of Geosciences, University of Edinburgh, Dummond Street, Edinburgh, EH8 9XP, UK
3 Global Academy of Agriculture and Food Security, University of Edinburgh, Easter Bush Campus, Edinburgh, EH25 9RG, UK
4 Geography, UCL, Gower Street, London, WC1E 6BT, UK

Corresponding author

Peter Alexander | peter.alexander@ed.ac.uk

Author contribution

All authors contributed equally to conceiving of the idea and drafting the manuscript.

Competing Interests

The authors declare no competing interests.

Acknowledgments

We would like to thank the UCL Geography Drawing Office for assistance with the diagram.