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How will minerals feed the world in 2050?

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ABSTRACT

By 2050, the world's population will have reached 9 billion. To feed that many people, soil fertility will have to be maintained artificially. All fertiliser materials depend on a geological resource: nitrogen (N) fertilizer production needs fossil fuels, and both phosphate (P) and potassium (K) are derived by mining. Irrespective of new biological techniques in plant breeding and genetic modification, soils still need to supply the mineral nutrients that plants require, and these are exported from soil with every harvest.

Studies of global offtake of N, P and K from soils through crop production show that although N and P are roughly in balance, removal of K from soils greatly exceeds inputs. World mine production of K needs to double to replace the amount removed in crops. Recent revision of reserve estimates for potash and phosphate rock show significant increases for phosphate rock and reductions for potash. Potash supply is now potentially of much greater concern than phosphate.

Against this background, it is clear that new potash mining ventures are required. In the developed world, the supply of potash from conventional sources will continue. However, in other countries the high price of potash means that novel unconventional sources are being considered. K silicate minerals (such as micas, feldspar and nepheline) have the potential to provide an adequate source of K for communities that cannot afford conventional fertiliser. However, it is not the total K content of these materials that controls their ability to supply plant nutrients, but the rate at which they dissolve.

1. Introduction

Food security is one of the greatest global 'grand challenges' of the 21st Century. The world's population reached 7 billion in 2012, and will rise to 9 billion in 2040 (median projection for growth; United Nations, 2014). The rate of change varies from one part of the world to another; the corresponding increase in the population of Africa will more than double from 1 billion to 2 billion over this period (Fig. 1).

A growing population requires a continuing supply of the essential raw materials, for construction, as fertilisers, and as raw materials for the manufacture of consumer goods. The global consumption of metals and minerals more closely correlates with GDP than with global population, reflecting links between the demands of a population with an overall increasing standard of living (Rogich and Matos, 2008). Demand for energy minerals (fossil fuels) is expected to peak, then fall, within the period 2010–2050 depending on the scenario used for modeling, and recognizing that alternative energy sources are available (Bentham, 2014; Hallock et al., 2014). There are no alternatives to mined materials for fertilizer manufacture.

In the context of food supply, the key plant nutrients are phosphorus (P), potassium (K) and nitrogen (N). P and K are mined as phosphate rock (dominated by minerals from the apatite group) and potash respectively. The term potash is used to describe the traded commodity, with grade (potassium content) given as equivalent % K_2O, and includes a number of evaporite minerals, mainly chlorides (sylvite, KCl; carnallite $MgCl_2 \cdot KCl \cdot 6H_2O$) but also sulphates (e.g. polyhalite, $K_2SO_4 \cdot 2CaSO_4 \cdot MgSO_4 \cdot 2H_2O$). In contrast, nitrogen is derived from the atmosphere through the Haber process. The availability of phosphate rock has received considerable attention in the context of 'peak phosphorus' (Cordell et al., 2009). In contrast, potash availability has received much less attention, despite the small number of producers and associated political controls on its supply (Rittenhouse, 1979; Manning, 2010).

This paper addresses the demand for P and K fertilisers through analysis of the amounts removed annually by harvesting crops ('offtake'), and then considers the availability of P and K in the context of estimates of known reserves and their global distribution.

2. Demand for P and K fertilisers

The amount of a fertilizer that is required is determined by the ability of a soil to provide the nutrient concerned. In general, farmers maintain the nutrient status of a soil so that crops can continue to be produced. Thus the amount of 'offtake' removed

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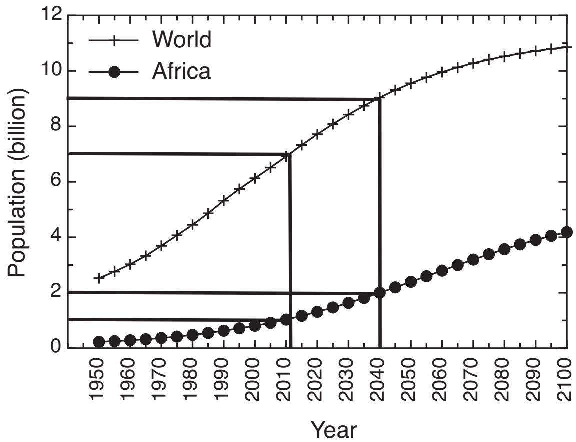

Fig. 1. Population growth for Africa and the World over the period 1950–2010, extrapolated to 2100.
Source: Data from United Nations (2014).

with each crop is balanced by the 'input' added by the farmer to maintain constant nutrient status.

A global evaluation of nutrient balances (Sheldrick et al., 2002) considers the overall requirements for N, P and K on a country-by-country basis for the latter part of the 20th Century. Using data from this study, Fig. 2 shows that offtakes of N and P globally are approximately balanced by inputs, which include composts, manures and crop residues as well as fertilisers. The situation for K is very different, with inputs from all sources being less than half the offtake (creating the 'potash gap'; Fig. 2). Fertiliser K inputs are typically less than 10% of the offtake. The low use of K especially in Africa is confirmed by statistics produced by the Food and Agriculture Organization of the United Nations, which show that Africa consumes just 1.5% of the world's potash fertilizer production, yet has 15% of the world's population (FAO, 2010). The evidence from nutrient balance studies indicates that while P is roughly in balance, K is being mined from the world's soils at a rate that far exceeds counterbalancing inputs.

To place the global assessment in a national context, the importance of balancing offtake and inputs in crops consumed in the UK can be illustrated by comparing potatoes and bananas. In 2011, the UK produced 6.3 million tons of potatoes from 146,000 ha of land (DEFRA, 2014a). Potatoes contain around 4 g K/kg, so the corresponding K offtake in the potatoes themselves (ignoring offtake in the foliage) is of the order of 25,000 T K or 29,000 T K_2O. The

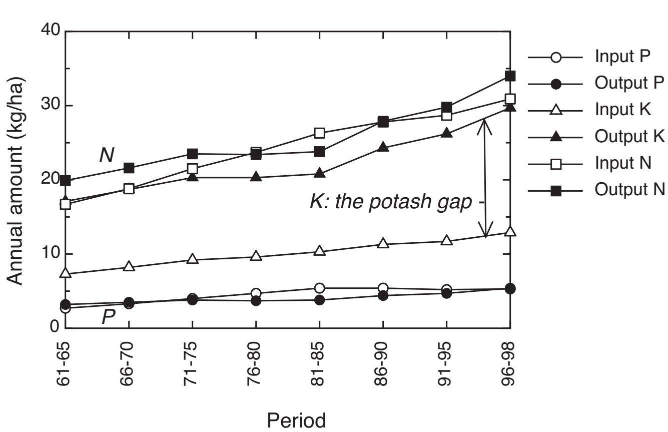

Fig. 2. Global nutrient balances for N, P and K, comparing outputs removed as harvest and inputs from all sources.
Source: Data from Sheldrick et al. (2002).

corresponding fertilizer input for 2011 was approximately 30,000 T K_2O (DEFRA, 2014a), which shows that offtake and fertilizer inputs roughly balance. The value of potash applied to produce potatoes is around US$10 million, or £6 million. The UK's consumption of bananas is approximately 1 million tonnes (DEFRA, 2014b), with a similar potash content to potatoes, so the corresponding value of the potash consumed as an import hidden within the crop is of the order of £1 million. What is unknown is whether or not the potassium removed from the soil where bananas are grown is replenished with an equivalent amount of K fertiliser.

3. Availability of P and K

Cordell et al. (2009) highlight the issue of 'peak phosphorus', arguing that P would become increasingly difficult to source in the early part of the 21st Century. In part these arguments were based on the cited reserves of phosphate rock, which are reported by the British Geological Survey and the United States Geological Survey (Table 1; Jasinski, 2014a). Recently reported figures for reserves and annual production rates can be used to predict the life expectancy of a mineral resource (Fig. 3). Importantly, there is a sudden increase in reserves, and subsequently in projected life, in 2010 (Fig. 3). This is due to revision of the way in which reserves of phosphate rock were calculated – the term 'reserve' is strictly defined to encompass the amount of material that can be mined profitably using present-day technology (USGS, 2012a). The constant values for projected life (around 100 years) over a period of 15 years indicates the way in which estimates of reserves are being constantly updated. It now appears that phosphate reserves will last 300 years. Bearing in mind that the concept of 'peak phosphorus' was introduced in 2009, it appears to have been overtaken by events.

In addition to revision of estimates of reserves, it needs to be born in mind that phosphorus is widely distributed as a commodity. Chernoff and Orris (2002) and Orris and Chernoff (2002) report over 1600 mines, deposits and occurrences of phosphate rock globally that are of economic interest. According to Jasinski (2014a), 16 countries produce 95% of the world's phosphate rock production, with 23 countries producing a significant amount.

Table 1
Production statistics and reserves estimates for phosphate rock (Jasinski, 2014a). All figures are in thousands of tons.

	2012	2013	Reserves
China	95,300	97,000	3,700,000
USA	30,100	32,300	1,100,000
Morocco/Western Sahara	28,000	28,000	50,000,000
Russia	11,200	12,500	1,300,000
Jordan	6380	7000	1,300,000
Brazil	6750	6740	270,000
Egypt	6240	6000	100,000
other countries combined	5500	5630	520,000
Tunisia	2600	4000	100,000
Peru	3210	3900	820,000
Israel	3510	3600	130,000
Saudi Arabia	3000	3000	211,000
Australia	2600	2600	870,000
South Africa	2240	2300	1,500,000
Mexico	1700	1700	30,000
Kazakhstan	1600	1600	260,000
Algeria	1250	1500	2,200,000
India	1260	1270	35,000
Senegal	1380	920	50,000
Togo	870	900	30,000
Syria	1000	500	1,800,000
Iraq	200	350	430,000
Canada	900	300	2000
Total	216,790	223,610	66,758,000

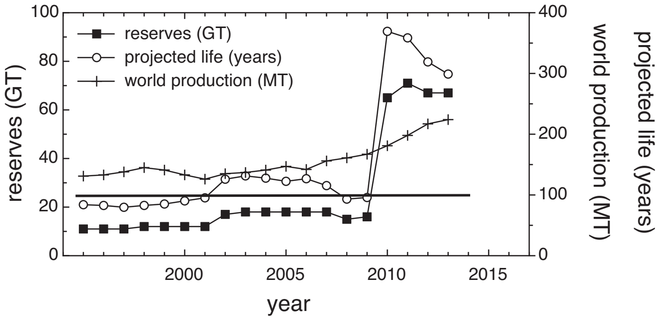

Fig. 3. Reserves, world production and projected life for phosphate rock.
Source: Data from Jasinski (2014a).

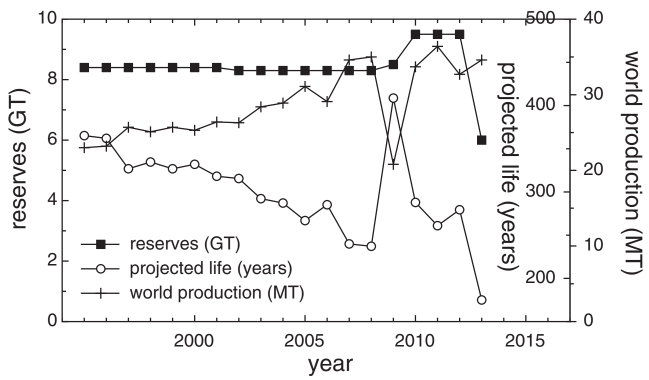

Fig. 4. Reserves, world production and projected life for potash.
Source: Data from Jasinski (2014b).

The availability of potash contrasts with that of phosphate. Declared reserves are very constant, between 8 and 9.5 GT, for the period 1995–2012 (Fig. 4), and then they dropped significantly in 2013 because of revised reporting (Jasinski, 2014b). There is a rising trend in annual production until 2009, and consequently a decrease in projected life, from 350 years to 175 years in 2013. In 2010, world production reduced by a third, and this immediately followed a maximum in the price (up to US$1000 per ton in some markets; Manning, 2010). The price of potash came back down to around US$350 per ton, and annual production returned to around 35 million tons.

The global distribution of potash is very different to that of phosphate rock. Potash production is dominated by five countries that produce over 80% global production (Belarus, Canada, China, Germany and Russia), and almost 50% of the world's reserves are located in Canada, with 30% in Russia (Table 2; USGS, 2012b). Thus global potash production is dominated by a small number of producers, giving rise to a range of political issues highlighted by Rittenhouse (1979). These continue to be reported in newspapers to the present day, especially concerning disputes over potash between Belarus and Russia.

Table 2
Production statistics and reserves estimates for potash (Jasinski, 2014b). All figures are in thousands of tons K_2O equivalent.

	2012 prodn	2013	Reserves
Canada	9000	10,500	1,000,000
Russia	6500	5300	600,000
Belarus	5650	4900	3,300,000
China	3900	4300	210,000
Germany	3000	3000	140,000
Israel	1900	2000	40,000
Jordan	1400	1200	40,000
USA	900	1100	150,000
Chile	900	970	200,000
Brazil	430	470	22,000
UK	460	460	300,000
Spain	425	436	20,000
Other			50,000
	34,465	34,636	6,072,000

4. Feeding the world in 2050

It is clear that the use of mined fertilizer minerals will continue for the foreseeable future, as this is essential to maintain crop outputs needed to feed growing populations. Despite concerns expressed about 'peak phosphorus', it appears as though inputs correspond to offtake (Fig. 2), and the declared reserves of P recently increased significantly, with a 300 year reserve horizon. The wide geographical spread of sources of P implies diversity in the supply chain, which in turn strengthens security of supply. Additionally, there appears to be abundant scope for recovery of P from wastewaters (de-Bashan and Bashan, 2004; Molinos-Senante et al., 2011), which broadens the resource base.

Fig. 2 suggests that inputs of potash need to at least double to close the global 'potash gap'. In contrast to phosphorus, potash is derived from a much smaller number of countries, predominantly north of the Equator, and it is not recoverable from waste waters or similar sources. There is therefore a need to identify new sources of potash in order to fill the 'potash gap', especially for poorer communities in the less developed world. However, the capital costs of developing a conventional deep underground potash mine are high, and need to be recovered from sales of the appropriately priced fertilizer product. In contrast, almost all phosphorus ore comes from open pits, which are much cheaper (but processing is more costly, being more energy intensive).

New conventional potash mines are being considered, with plans for a second mine near Whitby (UK) at an advanced stage (http://www.yorkpotash.co.uk), to join Boulby Mine (www.iclfertilizers.com) in working Zechstein evaporites. Other locations where deposits are known and mine planning is being or has been considered include the Congo (Pointe Noire; http://www.magindustries.com) and Thailand (El Tabakh et al., 1999; Hite and Japakasetr, 1979). In general, these are deep underground mines, given that the target mineral deposits are evaporates and so unlikely to be suitable for surface mining. There is no doubt that ventures of this type will be needed to ensure that the supply of potash increasingly meets the need to replenish offtake. However, it takes a very long time to bring a project of this type to production (the Thai potash deposits have been known for over 50 years, and no mine has yet been built). The most recent mineral statistics (Jasinski, 2014b) emphasize that potash is a cause for concern (Fig. 4).

There appears to be scope for unconventional sources of K for plant nutrition (Ciceri et al., 2015). In deeply leached tropical soils, soluble chemical fertilisers are rapidly removed from the soil, and so alternatives that slowly release nutrients may have advantages that do not apply in the soils of the glaciated northern hemisphere. With this in mind, Leonardos et al. (1987) state "Unfortunately, the standard concept and technology of soil fertilizer...is behind that of the superphosphate concept developed by J.B. Lawes in England, 150 years ago...Had this technology been originally developed for the deep leached laterite soils of the tropics instead for (sic) the glacial and rock-debris-rich soils of the northern hemisphere our present fertilizers might have been quite different." These authors suggest that potassium silicate minerals may weather sufficiently rapidly in tropical soils to release enough K to support plant growth.

Attempts to use potassium silicate minerals (K-feldspar, micas) as sources of K date back to as early as 1887 (Sanz Scovino and Rowell, 1988). In the UK the Cambrian Fucoid Beds have been considered (Bowie et al., 1966) and used (on a small scale) by organic farmers (sold as 'adularia shale'). However, results of crop trials with these minerals have yielded variable results (Manning, 2010), and Harley and Gilkes (2000) suggest that they will not be economically viable. Nevertheless, the recent high price of potash, and the need to supply K to land that is distant from readily available sources of conventional K, have led to increased interest in alternatives. The micas appear to be able to give crop yields similar to conventional KCl: Mohammed et al. (2014) show that equivalent applications of biotite and KCl give similar yields of leeks. Madaras et al. (2012) demonstrate that zinnwaldite (a mica associated with tin mineralization) is effective as a source of K for barley, as is acid-treated phlogopite for rice (Weerasuriya et al., 1993). These observations arise from the demonstrable ability of the micas to weather in soils, where they influence the availability of K through cation exchange (Mohammed et al., 2014). In contrast, framework silicates such as K-feldspar and nepheline release K through weathering of a three-dimensional covalent aluminosilicate network. The dissolution rate of the mineral determines the rate of release of K (Manning, 2010), explaining why positive results in crop trials have been obtained where nepheline syenites have been used as a source of K (Bakken et al., 1997, 2000); nepheline has a much higher dissolution rate than K-feldspar, by at least 2 orders of magnitude at near neutral pH (Palandri and Kharaka, 2004).

5. Conclusions

Nutrient audits of the dominant fertilizer inputs to soils (N, P and K) show that N and P are roughly in balance, whereas K inputs need to double to produce sufficient crops to meet the needs of the current global population. P is derived from geographically diverse geological deposits, and recent redefinition of reserves has greatly extended the life expectancy of the commodity. K is mined predominantly as evaporite minerals from a small number of countries and deposits, which restricts availability. The price of potash has fluctuated greatly since 2000, reaching $1000 a ton in some markets. Recent reevaluation of potash reserves gives cause for concern, and this has encouraged investigations of alternative sources of K. These include the potassium silicate minerals, of which micas have been shown to give similar results in trials in which they are compared with KCl. Potassium feldspars and nepheline syenites have also been investigated, with mixed results. Nevertheless, there are very few published rigorous trials involving these minerals in tropical soils, where they may have significant potential. Given the urgent need to sustain crop production as populations rise in the near future, alternatives to conventional potash fertilisers could well play a significant role.

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