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TOWARDS A CLOSED PHOSPHORUS CYCLE**

BY

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Summary

This paper stresses the need to address upcoming scarcity of phosphorus, a mineral nutrient that is essential for all life on Earth. Agricultural crops obtain phosphorus from the pool in the soil that can be replenished by recycling of organic material, or by application of inorganic fertilizer, originating from mines, largely concentrated in three countries only: Morocco/Western Sahara, China and USA. A complicating factor is that the phosphorus rock contains other substances as well, including the heavy metals cadmium and uranium. These substances currently end up in fertilizer and in phosphogypsum where they may pose threats to human and animal health. Hence scarcity and environmental considerations call for action to close the phosphorus cycle. The paper compares two options for intervention: mandatory recycling versus a ban on imports of contaminated phosphorus, and argues in favor of the second.

Key words: Mineral depletion, Sludge recycling, Uranium recovery, Soil contamination, Import dependency

JEL Code(s) Q16, Q53

1 INTRODUCTION

Quite a few minerals are essential nutrients for all life on Earth. They affect the growth, functioning and health of all living creatures, plants as well as animals. Whenever uptake of these essential minerals falls short of requirements, growth will be retarded. Children may develop symptoms ranging from stunting to mental retardation (Hetzel 1983). The amounts of essential nutrients required vary greatly by element. Phosphorus (P), potassium (K) and

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calcium (Ca) referred to as macro-nutrients, are usually needed in relatively large amounts, while requirements of the micronutrients zinc (Zn), copper (Cu), boron (B), molybdenum (Mo) are small but essential, nonetheless.

In agriculture, crops obtain their mineral nutrients from reserves in the soil, often supplemented with organic fertilizer from manure, animal bones and household waste as well as chemical fertilizer. Chemical fertilizer usually consists for a major part of nitrogen (N) captured from the atmosphere through an industrial process. Depending on the soil deficiencies prevailing and the needs of the crop to be grown, fertilizers vary in their composition, particularly of N, P and K, under the premise that available quantities of micro-nutrients will be sufficient, either because they are already present in the soil, or because the minerals used for fertilizer contain them anyway, due to the composition of the rock they were derived from. We remark that this assertion about micro-nutrient availability has increasingly come under scrutiny, particularly with regard to Subsahara Africa, where soils are heterogeneous and tend to lack some of the essential minerals (Voortman 2010).

Demand for mineral nutrients is mounting due to increased demand for agricultural produce in response to rising world population, increased demand for livestock products, and hence for animal feed, upcoming use of crops as biofuels, and as biomass for industrial use. Moreover, through trade and urbanization a larger share of produce ends up far away from the farm, leading to nutrient surpluses in the form of crop residuals, animal manure and human excrements in densely populated areas, and soil depletion on the fields the crop originates from, to be mended by application of chemical fertilizer. Finally, some the best lands increasingly fall prey to urban expansion, causing the boundary of cultivation to be pushed ever farther on marginal lands that by definition have higher deficiencies, if not of water then of nutrients (Young 1999).

Unlike fossil fuels that can eventually be replaced by renewable sources such as solar energy, mineral nutrients have no substitute, not now and not in the most distant future. Of course, the major difference from fossil fuel would be that nutrients are not truly lost in the process but form cycles. Phosphates in the soils do not flow out very quickly, and remain for most cultivated land available for future use (Hilton et al. 2010).

Yet, the harvested part of the crop leaves the area, and the rising distance from field to stable as well as from field to table makes it quite difficult to return mineral nutrients to their soil of origin. In fact, the water treatment plants that process urban waste generally see it as their major task to produce clean and safe drinking water, rather than to extract nutrients for recycling. Consequently, most of these end up in filters whose content is disposed in rivers, and eventually to be lost irrecoverably in the sea, or in landfills often bound in a chemical substance that does not allow reuse by agriculture.

In short, availability of mineral nutrients worldwide deserves attention.

In this paper we focus on P, for one because it is the scarcest among the macro-nutrients, has a particularly high supply concentration with only three major producers: Florida (USA), China and Morocco/Western Sahara. Furthermore, production in Florida is dwindling fast, China that harbors the largest reserves, considers its resources to be strategic in view of its future needs, and hence not for export, leaving only Morocco/Western Sahara as major supplier of the rest of the world, with a large number of small suppliers such as Finland, Israel, Jordan, Senegal and Togo producing for domestic use mainly. This scarcity has been noted for a long time (Asimov 1974; Herring and Fantel 1993; Smil 2000; Cordell et al. 2009; Gilbert 2009) but has so far not elicited much action.

A second reason to focus on P is the contamination of soils and from there food and humans with heavy metals and radio-active materials such as cadmium, thorium, uranium and its decay product radium (Fourati and Faludi 1988) that with present technologies go hand in hand with application of fertilizers of mineral origin. In this connection, we note that the uranium content is such that with the fast expansion of the nuclear energy sector, particularly in China and India, to reduce dependence on fossil fuel and their imports, and to meet the growing electricity demand, particularly in transport, it may gradually become profitable to reinvigorate the earlier practice that dates back to the 1950s when uranium was recovered from phosphoric acid, the main intermediate substance in production of phosphates for fertilizer, at the time to build atom bombs, now to fuel nuclear reactors. The uranium recovery processes picked up in the late 1970s and were more or less abandoned in the early 1990s as direct mining of uranium became more profitable (Guida 2008), with the consequence that most of the uranium stays in the phosphoric acid and currently ends up, jointly with the other materials either in the P-fertilizer itself or in the byproduct phosphogypsum (PG) that is used as construction material and as calcium- and micro-nutrient-rich fertilizer amendments. However, since the process generates as much as 1.46 ton of PG per ton of phosphate rock processed (Martin et al. 1999), PG-disposal is a serious issue and much of this byproduct is currently ending in stacks and landfills, partly because as long as the radioactive substances are not removed, other uses are considered too dangerous (EPA 2006). Beside the need to purify phosphates and PG, another, rather compelling reason for revisiting the recovery technology would be that the ratio of uranium in direct deposits relative to phosphorus rock is about 3/22 (Price and Blaise 2002).

About 85% of phosphorus rock is used for agriculture, 70% as P-fertilizer, 15% as direct supplement in animal feed (Hilton et al. 2010). Of the remaining 15% a small part is used in detergents, fire retardants as well as in firework, while the remainder ends up in food and drinks directly, such as cola drinks that own their brownish color and their good preservation properties to phosphoric acid. This direct use for human consumption derives from more subtle chemical processes that remove virtually all toxic elements. Phosphate fertilizers and animal feed supplements by contrast still contain a few percent of such substances that accumulate in the soil and in animal bones, and even when harmless—though most are heavy metals and some have a little radiation—get spread so thinly that recovery for industrial use will not be profitable any time soon. Since recycling replaces chemical fertilizer it reduces the influx of contaminants and, therefore, helps addressing both the scarcity and the contamination problem.

In short, both the scarcity and the contamination question need to be addressed by improved management of the P-cycle, only a small segment of which actually runs along an actual P-market, while waste flows and storage in soils largely constitute externalities that are seldom being taken care of through regulation.

After sketching the P-cycle in some further detail, we discuss two policy options for enhancing sustainable P-management, so as to make recycling more profitable, discourage overuse, and reduce to a minimum the content of toxic substances in chemical fertilizers. These management options should involve all major players: mines and processors; uranium recovery plants, crop farmers, livestock farmers, food and drinks industry, and urban waste and water treatment plants. Of course, in this delivery system the nuclear energy cycle presents dangers of its own, but these are already kept under the vigilant custody of the International Atomic Energy Agency, and fall beyond the scope of our present discussion.

The paper proceeds as follows. Section 2 gives some further details on P-availability and flows and Section 3 compares two options for sustainable P-management.

2 P-AVAILABILITY AND FLOWS

2.1 *Overall Availability*

As shown in Table 1, taken from Smit et al. (2009), P is a very common element. It in fact is the 11th most common element in the Earth's crust. However, its concentration is usually very low, far too low to be minable by industrial means. Indeed, agriculture is an age-old process to mine P as well as other nutrients from soils, via crop roots, usually through the intermediary of soil fungi (mycorrhizeae). Since P is removed with the crop, the stock in the soil has to be replenished, and until the middle of the nineteenth century this was done in two ways. One is to return animal manure, human excrements and crop residuals to the land, which, however, inevitably leads to some depletion, as it will never be possible to return all P that is removed. The other is to involve livestock, in particular ruminants, and use them as P-concentration machines that harvest grass, often from pasture land on which

TABLE 1 – MAJOR BIOSPHERIC RESERVOIRS OF PHOSPHORUS (FROM SMIT ET AL. 2009)

P reservoir		Total storage (MT;P)	Reference
R1	Sediments (crustal rocks and soil > 60 cm deep and marine sediments)	800–4,000 * 10^6	1
R2	Soils (0–50 cm)	40,000–50,000	2
	Inorganic P	35,000–40,000	2
	Organic P	5,000–10,000	2
R7	Minable P	2,400–6,600	3
	Ocean	93,000	2
R4	Surface, 0–300 m (total dissolved P)	3,000	1
R5	Deep sea, 300–3300 m (total dissolved P)	90,000	1
R3	Terrestrial phytomass	500–550	2
	Zoomass	30–50	2
	Anthropomass	3	2
R6	Marine phytomass	50–140	1
R8	Atmosphere	0.028	1

1 = Ruttenberg (2003), 2 = Smil (2000), 3 = Jasinski (2009).

no food crops will grow, and produce droppings for use on the arable land. By the same token it becomes difficult to achieve high yields in regions such tropical Africa where animal diseases and lack of vaccines prevent keeping ruminants.

The Inca civilizations for many centuries also used the massive bird droppings (Guano) accumulated throughout the ages along the coast of Peru, which is rich in N (because of the dry climate) and P. In 1802, Alexander von Humboldt studied the properties of Guano and made the substance known in Europe, where it became widely used as the first non-local fertilizer. However, since the Guano was rich in nitrates, it also became a raw material for the production of explosives, known as Chile salpeter, and the USA gradually established a monopoly over it.

In the course of the nineteenth century, new sources of N and P became available for fertilizer production. Throughout the world the beneficial long term effects of returning bones to the land had been recognized. For example, in West Africa it had always been the practice in many villages to plant a tree on a grave but in 1837 Lawes discovered in Rothamsted (Johnston 2008; Hilton et al. 2010) that water soluble ammonium phosphates from bones gave higher yields than any other water soluble ammonium salt supplying the same amount of N. On this basis he eventually worked out the correct strength of sulphuric acid, and the correct ratio of acid to bones: the chemical fertilizer industry was born.

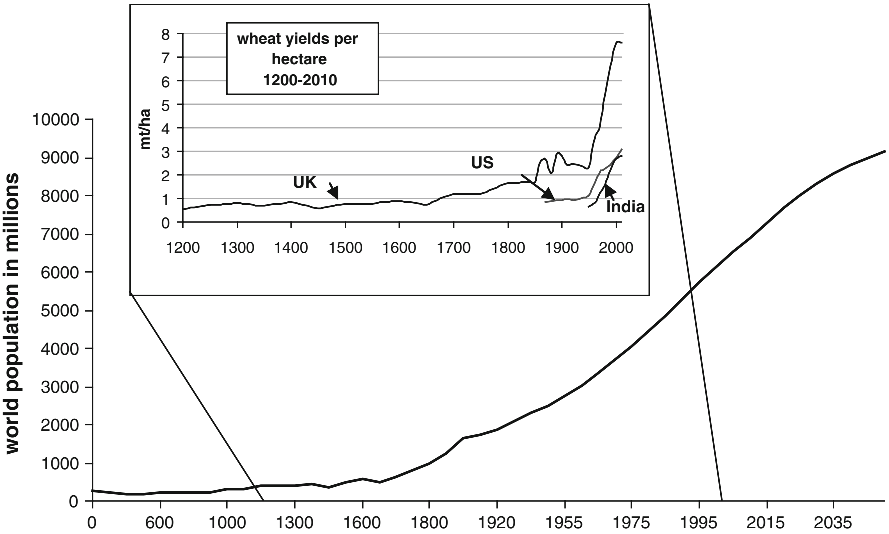

Figure 1 – World Population and wheat yields in metric ton per hectare. Population data are from the US Census Bureau and the UN World Population Prospects, medium variant, with world population expectedly rising to a maximum of about 9.5 billion around 2,050, and slowly falling afterwards. Yield data are for UK from Stanhill (1976) and Clark (1991); for India Department of Agriculture (2010) and USDA/ERS (2010), respectively. The yield graph shows that in the US yields only picked up after World War II, when chemical fertilizers became widely used, and in India in the 1960s with the Green Revolution when new short stem varieties combined with fertilizer became available

The introduction of chemical fertilizer marked the beginning of a fast rise in world population, made possible by a dramatic increase in the yield of main crops, particularly cereals (see Figure 1) that more than compensated for the loss of the best lands following urbanization. Of course, several other developments occurred in parallel, such as improvement in hygiene, hand washing in particular, and medical science (Kuznets 1965) and the "treatment effect" of fertilizer as such can not be isolated from this mix of events.

Nonetheless, with a present world population of about 6.5 billion expected according the UN population projections to rise to a maximum of 9.4 billion by 2050 and to remain about constant afterwards during this century, one would not even dare to imagine the small number of people that could be nourished, had the world to be fed with present day technologies but without mineral P, particularly because half of the world population is already today living in urban areas that do not return their wastes and excrements to the land, all this irrespectively of whether their food originates from the other side of the planet or from the field nearby. At the same time, the intensive livestock sector that often procures animal feed from other parts of the world is currently injecting P in soils that are already amply saturated with it.

Empirical evidence (Johnston 2008) suggests that this P will in general not be lost, except on soils that are explicitly P-fixating, because phosphates unlike ammonium substance are poorly soluble in water, do not evaporate and essentially only leave the land via sediment flows.

2.2 *Mining*

For chemical fertilizer, the cycle starts with the open pit mining of phosphorus rock from deposits of sedimentary origin. Table 2 shows the current production, the known reserves and the reserve base. Reserves are deposits that are currently exploitable in an economically viable way. The reserve base consists of deposits whose exploitation could conceivably become viable at higher prices or with significantly improved technology. Hence the concept is inevitably flexible.

The estimates of the reserve base vary among sources. Table 2 reaches a total of 47,000 Mt, Gilbert (2009) arrives at 52,000 Mt, and the Florida Institute of Phosphate Research at 66,750 Mt, following an increase in China's reserves (Hilton et al. 2010). Depending on the reserve base estimate, this

TABLE 2 – WORLD PHOSPHATE MINE PRODUCTION, RESERVES AND RESERVE BASE IN MILLION TONS P_2O_5, 2009 USGS ESTIMATES

	Mine production (Mt)			Reserves (Mt)	Reserve base (Mt)
	2006	2007	2008		
Australia	2	2	2	82	1,200
Brazil	6	6	6	260	370
Canada	5	1	1	25	200
China	31	45	50	4,100	10,000
Egypt	2	2	3	100	760
Israel	3	3	3	180	800
Jordan	6	6	5	900	1,700
Morocco & W Sahara	27	27	28	5,700	21,000
Russia	11	11	11	200	1,000
Senegal	1	1	1	50	160
South Africa	3	3	2	1,500	2,500
Syria	4	4	4	100	800
Togo	1	1	1	30	60
Tunisia	8	8	8	100	600
United States	30	30	31	1,200	3,400
Other countries	8	8	11	890	2,200
World total (rounded)	142	156	167	15,000	47,000

Mt, million metric ton Jasinski (2009).

Source: For definitions see http://minerals.usgs.gov/minerals/pubs/mcs/2009.

means that at present use the estimated reserves will last for 100–150 years, and the reserve base for 300–350 years. Comparison with Table 1 shows that the reserve base is about as large as the stock in the soil.

These numbers seem to leave moderately comfortable room for use by future generations but they discard population growth and rise in per capita demand. Furthermore, relative to fossil fuels and other non-renewables, the saving grace for P is that it belongs to a cycle that could actually be closed if not now then in the future. Unless it flows into the oceans where it gets diluted, or is burnt at such high temperatures that it no longer is biodegradable, P is in its very essence recyclable.

Indeed, the intricacy of the subject of P-management might well be linked to the illusion of a relatively long horizon until full depletion that, however, becomes dramatically shorter once growth in demand is being accounted for. For example, if as anticipated by FAO (2009) food production were to double from now until 2050, following the rise in population and in per capita income, to reach a constant level soon afterwards, the time until depletion comes closer to 80–100 years (see also Smit et al. 2009, for explicit calculations), all this even disregarding the current rise in use of crops in biofuel (Keyzer et al. 2008), and the necessary expansion into marginal lands that need more P. At any rate, whatever the exact figures and growth rates assumed, they leave little doubt that the system has to change, that resources must be preserved for later use and that lavish application of chemical P has to end.

2.3 *Processing and Waste*

The P-rock is generally processed very close to the mine, because it is quite bulky. The extraction process essentially consists of treating ground rock with sulphur oxide, so as to produce phosphoric acid, from which the actual fertilizer is produced as soluble phosphate salt after reacting with calcium, often jointly with N and K. As mentioned earlier, phosphogypsum is the main byproduct. Contaminants flow into fertilizer as well as phosphogypsum.

Uranium recovery can be effectuated from phosphoric acid, through a dedicated process within the fertilizer plant, extracting up to 95–99%. Removal of other contaminants would need similar intermediate steps.

We may note in this connection that the fertilizer industry largely originated after World War II from reconversion of production lines for explosives to civilian use. This largely explains the industry's capacity to supply in the wake of the war fast rising quantities to the US and Europe as well as to Asia when the Green Revolution set off. Furthermore, in view of these military connections it was only natural in the late 1940s when atom bombs had to be developed for the US to turn to its fertilizer factories. And clearly, a sector that was originally dedicated to weapon production will take some time and change of culture until it starts paying much attention to the removal of toxic substances.

Internationally, trade nowadays is almost exclusively in inorganic P, largely and increasingly as the final product fertilizer, produced close to the P-mine or shipped to the ammonia plant at a site where energy is available at low cost, often close to oil refineries. Yet, its whereabouts are not easily traced, because of the diverse nature of the compounds it belongs to. Yet, in view of the nuclear applications and the dangers of proliferation, the IAEA recently expressed interest in tracking such flows. Largest importers are OECD countries, India, China, Thailand and Brazil (UN comtrade 2010).

2.4 *P-Utilization in Agriculture*

Whatever its origin, P almost always reaches the plant via its roots within the soil. Fertilizer application is a mere replenishment of the P-pools of various soil layers, not a direct input into the crop itself. Combined, the soil and crop type determine how much P the plant can access under specified humidity and temperature conditions.

Hence as far as P and K are concerned a farmer may choose to refrain from fertilizer for quite some time, until stock depletion becomes limiting. For N the situation is different since it can evaporate and is more easily washed out by water. Farmers are always well aware of the fact the most constraining nutrient will be the limiting factor on their crop yield. Consequently, as long as NPK are provided in relatively fixed and inflexible proportions, and fertilizer is not too expensive, risk avoidance will induce them to be safe on the N side, and hence overuse P and K. As some put it: “Waste is the fertilizer industry’s best customer”.

In addition, precisely because they impact on stocks rather than on flows, P and K application and soil fertility in general tend to be decisively affected by institutional circumstances. The nutrient pools in the soil are only valued in monetary terms via the land price under rental and the land price under sale. Therefore, a tenant who expects eviction by the landlord, or anticipates abandonment of the farm, will tend to mine the soils rather than keeping up the stocks. This also makes it hard to anticipate the impact of a rise in fertilizer price, both on production and on the soil, particularly because there is no futures market for it, and because land markets in rural areas tend to be very thin, albeit less with respect to rental than to sale (Binswanger et al. 1995).

Obviously, contamination with substances such as uranium present in the parent rock occurs whenever P of mineral origin is being applied. In fact, one of the secrets best kept from the general public is that as one buys a bag of fertilizer in a garden centre, the description on the label at best covers 60% of total composition since it only refers to N, P and K as such. Including the calcium, oxygen, hydrogen directly of the relevant chemical compounds one arrives at about 98% of the total weight. The question is what the remaining 2% are about. Not providing a full account keeps the customer under the illusion of exclusively buying N, P and K plus some neutral substance such as calcium. Like for pharmaceutical products, one is left with the idea that this neutral material is perfectly harmless and needed for texture and possibly to regulate smooth absorption, not with the impression that it is there because it would be too expensive to remove it. Fluor used for toothpaste and fluoridation of water also originates from the phosphoric acid industry and therefore also contain such byproducts (Bryson 2004). Even the micronutrient content that will tend to have a beneficiary impact gets little exposure. The same applies to the additives in animal feeds.

2.5 *P-Outflow To and From The Cities*

Whereas livestock generally—but not in The Netherlands—lives in rural areas that make good use for its manure to fertilize crops, and crop residues that remain on the farm also tend to be returned to the land, directly or as ashes, all produce sold on the market leaves the area never to return. A significant fraction (roughly one quarter) gets spoiled on its way to the consumer and ends somewhere as garbage in a landfill, rather than as animal feed or compost. Animal bones and offals are partly returned but following the outbreaks of various animal diseases such as BSE, and also in view of the content of heavy metals such as cadmium, regulations have become tight in most developed countries, requiring disposal in landfills, often even after incineration at such high temperatures that any future recovery of P from the ashes is excluded.

Clearly, most of the nutrients in food eventually flow, via the toilets, into sewage systems. What happens to it next is only known to few. Some cities flush directly into the river or into large reservoirs, others actively engage in water treatment before the water is being released, but in virtually all cases the concern is with health and sanitation (e.g. hand washing, CDC 2009), only rarely with conservation or return of mineral nutrients. In practice the substances obtained from the filters are generally dumped into landfills possibly after incineration, often with the motivation that their content of heavy metals and other toxic substances is too high to warrant reuse.

3 TOWARDS SUSTAINABLE P-USE

3.1 *P-Markets*

So far, the actual market of P was hardly referred to, and a question that may come to mind is to what extent the P-market currently provides the correct signals for intertemporally efficient allocation. For about thirty years the world phosphorus prices have varied very little except briefly during the 2007–2009 commodity boom, when supply shortfalls in Florida and Morocco triggered an export ban from China and caused the spot prices to rise temporarily from USD 50,-/metric ton to USD 450,-/mt and currently back to about USD 70,-/mt.

Not more than twenty percent of chemical P is currently being traded on the spot market, as most supply is directly channeled to the fertilizer producers, where a compound is formed with other commodities and the P-price can no longer be isolated. Relative to agricultural commodities, fertilizer production is a continuous process in hands of a by comparison small number of companies, and fertilizer sales are usually under longer term contracts between the mines and the fertilizer producers, with the mining (Morocco/Western Sahara) and the nitrogen and sulphur supplying countries (e.g. Saudi Arabia via its refineries) gradually increasing their share.

In 1991 the Chicago Board of Trade set up a future market for phosphates, so as to improve price disclosure but the spot market proved too thin to accommodate it, and the future market was discontinued in 2008. As a result the P-market currently is lacking clear price signals, particularly regarding scarcity in the future.

Add to this the fact that the flows of organic P (from crop residuals, animal manure, human excrements, sludge at water treatment plants, bones at slaughterhouses) are very bulky and barely traded on any market at all, and that as was discussed earlier P-fertilizer is not a direct input into production but merely a stock replenishment, and it will be less than a surprise that an inefficient and unsustainable resource allocation is the result.

3.2 *Options*

The discussion so far suggests that three problems need addressing: (i) the lack of targeted use of fertilizer by which the farmer is actually fertilizing the crop rather than the soil and tends to overuse P and K; (ii) the lack of recycling from cities; and linked to it (iii) the contamination of soils by substances present in the parent P-rock.

Much of the same applies to K. It contains similar byproducts, albeit in lower grades. Supply of K is wider and less concentrated geographically but the development of new mines is more costly and K recycling and purification are, therefore, relevant as well.

Recycling has to come from changed agricultural practice, particularly regarding more targeted application of nutrients to crops, better use of crops residuals and animal manure, but also and increasingly from returning the nutrients discharged in the cities to the rural areas, especially at sewage and water treatment plants but also at incinerators and at slaughterhouses. In parallel, there is need to develop technologies for cleaning both fertilizers and sludge and for isolating their heavy metals. Some of these measures are costly and need large investments with long gestation, hardly the most attractive high return investment project.

Another major hurdle would be that P-recycling tends to meet strong psychological resistance as the urge to stay clear of the human excrements is firmly rooted in all cultures, with compelling hygienic justification, and equally deeply engrained in every person beyond toddler age. Hence, the recycled product—referred to since 1991 as biosolid after a consultation of the public, Sludge News (2010)—has to be odorless, to be made free of all pathogens and to be only one ingredient of the NPK fertilizer compounds, so as to provide for a chemical composition that suits the crop and the land to which it is applied.

Assuming that these psychological barriers can be overcome, relative prices become the critical issue. Phosphate of mineral origin will only be able to keep its edge over recycling, its competitor, as long as its price is so low. Of course, enforcement of purification requirements that reduce the content of undesirable byproducts in fertilizers is desirable in its own right but in addition it also has the interesting positive side effect that by internalizing the externality of pollution, it can raise the cost of mineral fertilizer to farmers, by this inciting them to save on nutrient use as such, and making it easier for the competing recycling technology to expand. Indeed, since the number of phosphate exporters is so limited, most countries import their phosphates control of fertilizer quality will mostly be needed at the country border only, and becomes relatively easy. Such a regulation may have to be accompanied by cooperative agreements with the countries of origin i.e. principally with Morocco/Western Sahara, to remove undesirable substances close to the mines and to contribute to their valorization.

We now consider two options for intervention to affect the competitiveness of recycled P relative to "fresh" P: a mandatory recycling in cities, versus a ban on imports of contaminated P.

Mandatory recycling in cities. In the face of upcoming P-scarcity it might become tempting to introduce a regulation whereby water treatment plants would be forced to recycle their sludge in a productive way, and similarly for other forms of organic urban waste. Implementing such a regulation would be relatively easy, since the water treatment plants and garbage collection tend to be semi-public companies, while slaughterhouses are usually local monopolists. All can easily charge their customers for the additional cost. The regulation would also help shifting the price of the recycled waste down to the present level of mineral phosphates, and could presumably count on the support by farmers, since it would not increase their cost of cultivation. Yet, this would provide the wrong incentive as it would discourage investments into the recycling infrastructure and industry, and not reduce the often excessive rate of fertilizer application.

Ban on imports of contaminated P. Imposing a ban on imports of contaminated P (and K), would stop most of the inflow of pollutants into the soils, leaving the more localized discharges from industry as next target for regulation. This would force the fertilizer suppliers to remove most of the heavy metals and other toxic substances. Experience with uranium recovery has shown that this can be done up to 95–99% for uranium, and for other elements similar strategies can be designed, at a cost. Yet, since full removal of all byproducts is technically infeasible, it all depends on the severity of the ban how costly this removal will be, and hence how much recycling it will induce. Nonetheless, simply charging farmers with the increased cost of fertilizer purification might not be the best measure, particularly because phosphates are applied to the soil and not to the crop, meaning that a cost increase might incite farmers to save on purchase and to prefer mining the soil for a prolonged period. This is where the linkage with nuclear energy comes to the fore. Clearly, the nuclear energy sector would gain from restrictions on the free disposal of uranium via fertilizers, since it would force the mines and fertilizer producers to process their waste further and through this lower the cost of nuclear fuel. Similarly, the water treatment and sewage disposal plants would finally face a good market demand for their sludge, provided they can process it into safe and sufficiently homogeneous substances.

Hence both the urban water-sanitation sector and the nuclear power stations would gain and anyway both would be able to charge their consumers for any incremental cost. Therefore, the preferable policy mix might well be to tax these utilities a little, so as to help financing the infrastructure development for recycling, to compensate farmers in a lumpsum way, that is independently from actual fertilizer purchases, and possibly during a limited period of time, for the cost increase they incur, and to stabilize the revenues from recycling itself, so as to make investment in these sectors more attractive and less dependent on public subsidies.

In short, the regulatory modalities seem rather subtle, but the synergies appear to be significant. Anyway, irrespectively of whether the nuclear renaissance materializes as the developments in China and India would suggest, from the long term perspective on food and agriculture, for P sharply targeted use combined with large scale recycling is a must.

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