ISSN 2231-0584

Phosphorus: A Limiting Nutrient with Limited Resource

Akanksha Mishra
Environmental Science, Kamala Nehru College
University of Delhi

Introduction

Today, our society is in the middle of a web of environmental crises, ranging from shortage of safe drinking water, declining water table, lack of clean air to breathe and depletion of both non-renewable and renewable natural resources. We, the humans, can solely be held responsible for all of them because we need natural resources to fulfil our daily requirements of food, energy and rapid urbanisation. Despite such exploitative ways, we are not able to provide food security to a large population of the world. Food security exists when all people, at all times have access to sufficient, safe and nutritious food to meet dietary needs for an active and healthy life (FAO 2005a). A good supply of food, both in terms of quantity and quality has to be ensured to get food security for all. Apart from the basics of water and energy, fertilisers play a critical role in enhancing the quality of food crops. The NPK (nitrogen, phosphorus and potassium) fertilisers are the most commonly used ones. The NPK denotes three of the most important elements required for the growth of plants. Phosphorus (P) is particularly important for root growth and strengthening tissues found in stems and stalks. P is also involved in life sustaining crucial processes as phosphoglycerate molecule trapping carbon in Calvin cycle and forms the structural components (phospholipids) in cell membranes of plants. Not only that, it is also essential for human beings where it is present as hydroxyapatite in bones, (Ruttenberg 2007), as energy transfer medium in high energy bonds in Adenosine Triphosphate (ATP) and in the double helix DNA structure of genetic material, constituting ~1% of human body weight. All this phosphorus is made available to humans from soil, through plants.

The limiting nature of phosphorus

Soils are the only supplier of P in food chains beginning with plants (producers). The exchange of P between soil and biota occurs over a shorter time scale of 13 years with the average residence time of P in soils to be 600 years (Filipelli 2009). Indian soils are generally deficient in phosphorus (FAO 2005a; FAI 1989). This natural deficiency in soil can be due to many reasons; the inherent low levels of P (the crustal abundance of P is 0.1% (Nriagu and Moore 1984), the presence of P in the non-available forms or occluded forms and most importantly even when the available forms (fertilisers) are added to soil they immediately change to insoluble forms leaving a small time window of a few hours for plants to absorb the phosphate (Figure 1). Traditionally, farmers used animal and human wastes and other P rich sediments to replenish the soil with this relatively rare

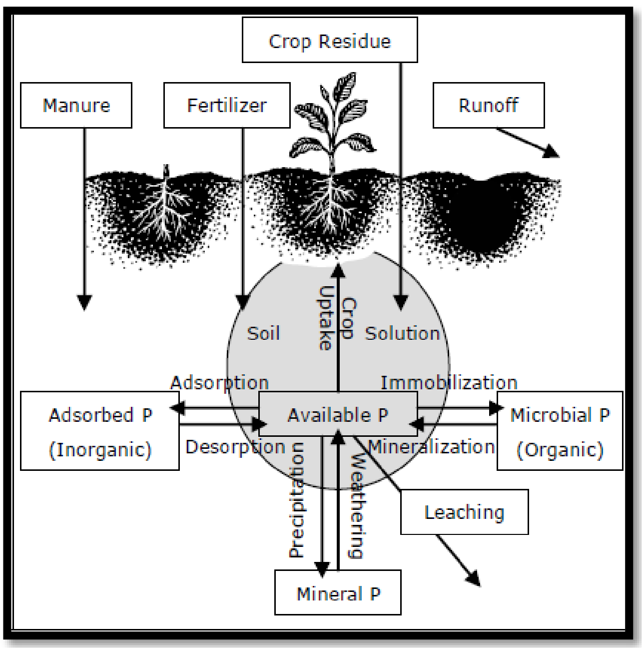

Figure 1: A simplified Phosphorus cycle in soil (Source: Hyland et al. 2005).

element in nature (Clabby 2010). Nowadays fertiliser application is the way to compensate for it. The understanding of the role of microbes in solubilising the precipitated P and making it available for absorption by plants can be a crucial (Richardson & Simpson 2011).

In natural systems, weathering of rocks provides P to soil. The obtainability of P through weathering is a slow, complicated process and depends on several factors like P content of the rock, climatic conditions, and the presence of P binding compounds. Although, P cycles itself in nature like other elements (Carbon, Nitrogen and Sulphur), its biogeochemical movement is different from them, as P containing rocks are the major reservoirs and the gaseous phase involved is minimal, making it a geological cycle (Figure 2). The time taken for one complete cycle of P is very long, in order of almost 0.1 Giga years (Gy) (Slansky 1980). It is this long duration which makes the flow of P from phosphate rock to ocean beds unidirectional for all practical purposes and hence makes P a non-renewable resource of importance (Figure 2). This non-renewability of phosphate rock can be compared to that of petroleum (Cordell et al. 2009; Dery & Anderson 2007).

As observed in various studies done across the globe, P is an important productivity determining nutrient for any ecosystem (Herbert and Fownes 1995; Parfitt et al. 2005; Schimel et al. 1994; Schindler 1977; Stevens and Walker 1970; Walker and Syers 1976). In a terrestrial ecosystem, the new soils are generally rich in rock derived nutrients like calcium, magnesium, potassium and phosphorus and are limited by atmospherically obtained nutrients such as nitrogen and carbon but with time, they adapt with some atmospheric nutrient fixing mechanism and then, the geologically derived nutrients like P becomes limiting (Chadwick et al., 1999). In an established, stable ecosystem, the average concentration of P in soil is 0.09% (Nezat et al. 2007) or 380-1330mg/Kg in upper 15cm of soil (Soon 2008) and the amount of available P is even smaller, not more than 0.01% of the total soil P.

The transfer of P from terrestrial to aquatic (lacustrine and riverine) systems occurs through leaching of soils, soil erosion and harvesting of crops (Martens and Rotmans 1999) wherein its behaviour varies due to stagnant or fluvial nature of water body. In rivers, the P is either carried away as soluble or particulate phosphorus. The soluble P is available for absorption of aquatic plants whereas particulate P adheres to smaller sediment particles which can be made bio-available later. The bio-available P in sediments help make fertile agricultural land out of flood plains. The lakes on the other hand make a perfect environment to study the different aspects of P cycle like fractionation, coupling-decoupling of P with other elements, microbial and phytoplankton absorption and desorption reactions as they are a confined ecosystem and especially important for understanding nutrient limitation in case of N and P, also known as cultural eutrophication (Ruttenberg 2008). The lake ecosystems have also been used to decipher the past changes in climate of the catchment region (Srivastava et al. 2013).

In oceans, the distribution of P is stratified i.e., the variation is found in both horizontal and vertical profiles of ocean. Alfred Redfield et al., (1963) has identified the molar ratio of C: N: P as 106C: 16N:1P to understand the ideal system and nutrient limitation. The ultimate P removal from the system is controlled by the burial of sediments with organic matter as their primary content. With the subduction of oceanic plate, the P is recycled into the mantle with carbon and nitrogen. Sedimentary organic phosphorus, is likely to be incorporated into the crystalline apatite during subduction zone metamorphism. As a result, subducted organic P does not return to the earth’s surface at the same rate as carbon and nitrogen and thus the phosphorus cycle is decoupled from that of carbon and nitrogen during subduction and metamorphism. This crystallized mass upon exposure gets weathered to produce bioavailable phosphorus (Ruttenberg 2007; Guidry et al. 2000).

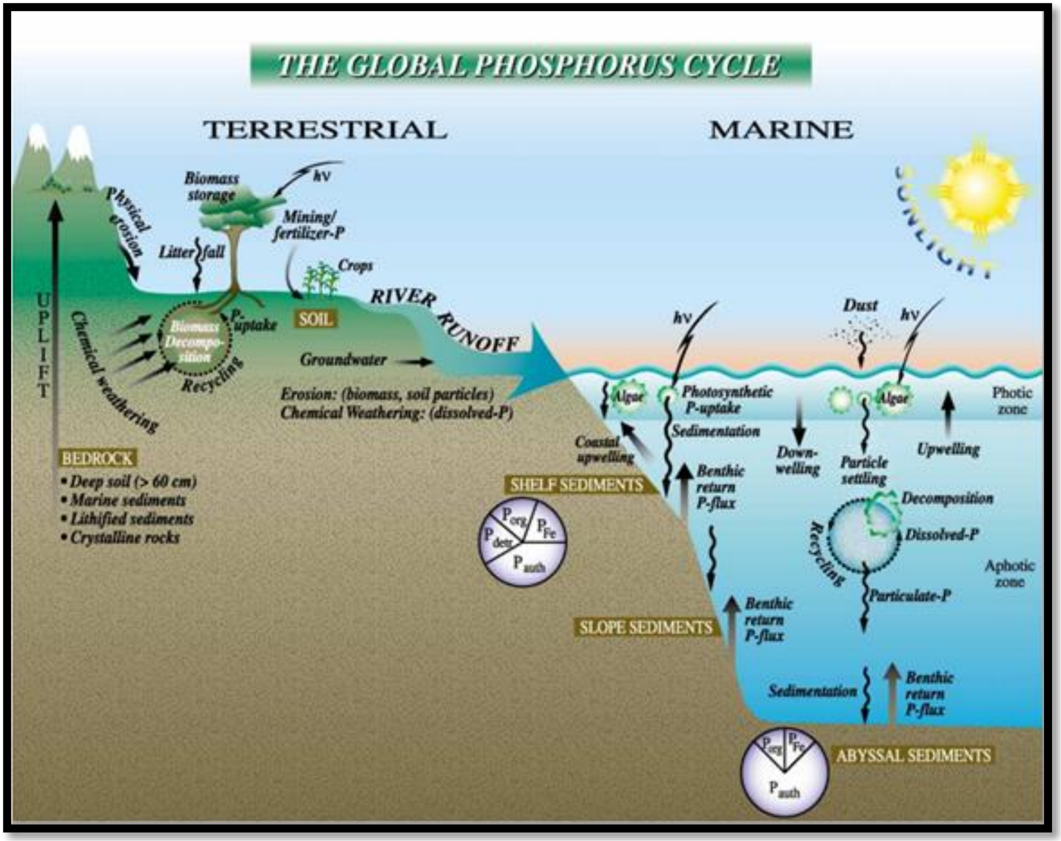

Figure 2: Diagrammatic representation of Phosphorus cycle (Source: Ruttenberg 2008).

The Phosphorus Resource

Phosphorus (P) in terrestrial and aquatic mediums is most commonly found in combination with oxygen as phosphatee[PO4]3- ion. Nearly all dissolved and particulate forms of P are combined, complexed or slightly modified form of this ion (Jahnke 2000). In the mineral form, P is found in combination with calcium as mineral apatite, accounting for 95% of P on earth (Jahnke 2000). Most of these phosphate deposits found in nature are sedimentary in origin and provides 82% of the world's phosphate production (Howard 1979). These sedimentary deposits are mostly of marine origin formed by organic material at the seafloor (Follmi 1996). The other minor reserves include the guano deposits, the droppings of seabirds, bats and seals.

The phosphate fertilisers are manufactured mainly from phosphate rocks. About 90% of the world-wide demand for rock phosphate is for food production through fertilisers (Smil 2002; USGS 2008). The rock phosphates have been used for manufacturing fertilisers since the beginning of the 20th century, but their consumption observed a peak after the Green Revolution. With no substitute and limited resource availability, P would play a crucial role in attaining global food security. In other words, we are all dependent on mined phosphate rock for fertiliser supply. The existing growth rate of population, increasing demand for food exerts pressure on exploitation of phosphate reserves. The global Phosphorus Research Initiative led by Swedish and Australian scientists estimated that the existing phosphate rock reserves would last for another 30-40 years (Clabby 2010). More importantly, the distribution of phosphate rock reserves across the world is highly uneven (Figure 3). The major reserves are lying with, USA (27%), China (17%), Morocco and Western Sahara (17%) and some smaller reserves with Jordon, Syria and other countries (UN 2005). When the reserves are so concentrated, a handful of countries can govern the global markets. In 2008, China increased its export tariff on phosphates by 135% to discourage export and secure its domestic supply (Fertilizer week 2008) increasing the price of fertilisers in the international market (Cordell 2011).

Like the production, the demand is also variable. In some of the developed countries, the demand for phosphates have stabilised as the soils have already crossed critical levels of P and require only lighter applications (Cordell et al. 2009). On the other hand, the developing nations like India and South Africa are amongst the worst affected where the demand for phosphates would continue to rise in near future due to natural P deficiency in soils. There, the over-application of fertilisers is also a cause of concern that result in accumulation of P in soils and the excess is drained to the water bodies leading to eutrophication (Gunther 1997; Steen 1998).

The application of fertiliser in Kg/hectare of arable land is much higher in India than the world average (World Bank 2016). According to Smil (2000b) five times more P is mined than what is actually consumed by the humans in food as almost 55% of the phosphorus is lost between farm and fork, due to which a large portion of P ends up in water bodies and landfills enhancing the threat to sustainable use of phosphate reserves. The process of mining and processing of phosphate rock has its own drawbacks. The amount of water and acids used is huge, which in turn produces large amount of mineral residues in the sands and clays (Straaten 2008). Some of the phosphate rocks even have elevated concentrations of cadmium, arsenic and certain radionuclides (Mortvedt and Beaton 1996) which if not removed properly can get into food chain.

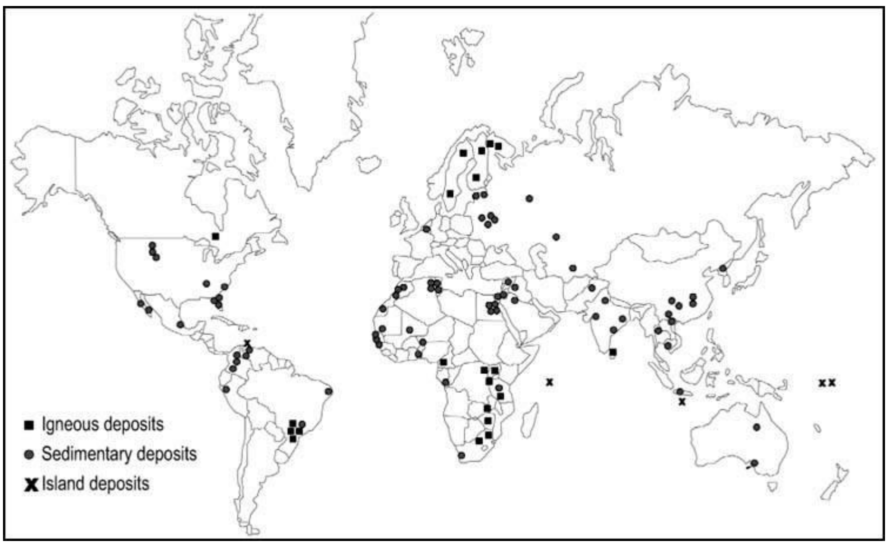

Figure 3: Map of Phosphate deposits across the world (Zapata, 2004; Source: http://web.mit.edu/12.000/www/m2016/finalwebsite/solutions/deposits.html.

Indian scenario

India is primarily an agrarian country with agriculture contributing to 22% to its GDP. With 20 agro-ecological zones, a large variety of soils are found here, and these soils suffer from degradation of various degree. The use of fertilisers began in India in the early 20th century. Its use observed a major hike after the introduction of High Yielding Varieties (HYV) of crops. For phosphate, the most common form of fertiliser used is di-ammonium phosphate (DAP) constituting 63% of total P2O5 consumption, other complex fertilisers' makes 27% of the usage and the remaining 10% is single superphosphate (SSP) (FAO 2005b). The reserves of phosphorus in India required by industries are mainly present in the form of apatite in the states of Andhra Pradesh and West Bengal and rock phosphate in the states of Madhya Pradesh and Rajasthan. Of all the requirement of phosphate fertiliser in India, only 10% is met by the indigenous sources, for the rest, we are dependent on imports from other countries (India Minerals Year book 2015). Currently, India has joint ventures like JIFCO with Jordan, IMACID with Morocco, TIFERT with Tunisia and is working in cooperation with Syria, Russia and Indonesia for import of phosphates (Department of Fertilisers, GoI 2015).

ISSN 2231-0584

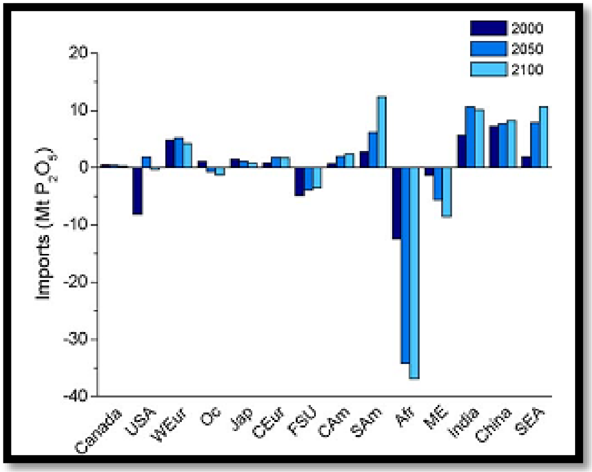

Figure 5: Expected trend of net import and exports of phosphorus in India along with different world regions (Source: Vuuren et al., 2010).

Dependence on other countries for the imports makes India more vulnerable to the vagaries of international market (Figure 5). Something like phosphorus, which is an essential element for all living organisms and a non-renewable resource as well, need strategic conservation attempts to sustain its availability.

Conclusion

The essentiality of phosphorus for living forms drives not only environmental, but political and economic concerns as well. In Indian context, the application of fertilisers is highly imbalanced, especially when India relies heavily on imports of phosphate rocks for manufacturing fertilisers. A strategic approach to field application as well as conservation methods is the key to future sustainable use. This is possible if fertilisers' application on fields is scientifically tested and only the required amount is used. The use of new technologies of fertilisers application is pertinent, as the increase in international price would hike the per unit cost of food production, which a country like India, with large population living below poverty line cannot afford. A better understanding of the sub-soil processes and conservation of phosphorus leakage from fields to aquatic bodies can hold the P in soil and hence prevent eutrophication. The P that gets dumped with the waste in landfills and the use of P in other chemicals and detergents should be discouraged. Above all, with all the efforts put in place the P would still remain a non-renewable resource, by attempting all the conservation efforts, we can prolong the duration of its usage. Unlike petroleum, there is no replacement of phosphorus in living beings.

References

Chadwick, O.A., Derry, L.A., Vitousek, P.M., Huebert, B.J. and Hedin, L.O. 1999. “Changing sources of nutrients during four million years of ecosystem development” Nature 397: 491–497.

Clabby, C. 2010. “Does peak phosphorus loom” American Scientist 98, no.4: 291.

Cordell, D. and White, S. 2011. “Peak Phosphorus: Clarifying the Key Issues of a Vigorous Debate about Long-Term Phosphorus Security”. Sustainability 3: 2027–2049.

Cordell, D., Drangert, J. O. and White, S. 2009. “The story of phosphorus: Global food security and food for thought” Global Environmental Change 19: 292–305.

Department of Fertilisers, Government of India, Accessed on 21st September, 2017 (http://fert.nic.in/page/joint-ventures)

Dery, P. and Anderson, B., “Peak Phosphorus” Energy Bulletin. Accessed on 13th August, 2007. http://www.resilience.org/stories/2007-08-13/peak-phosphorus.

FAI, Fertiliser and agriculture statistics (New Delhi, Fertiliser Association of India, 2003/04).

FAI. 1989. Soils of India. New Delhi, Fertiliser Association of India.

FAO. 2005a. Fertiliser use by crop in India. Rome, Food and Agricultural Organization of the United Nations.
FAO. 2005b. The special program for Food Security. Rome, Food and Agricultural Organization of the United Nations.
Fertilizer Week. 2008. Industry ponders the impact of China's trade policy. Thursday Markets Report, British Sulphur Consultants, CRU, 24th April 2008.
Filippelli, G.M. 2009. "Phosphorus cycle" in Encyclopedia of Paleoclimatology and Ancient Environments, ed. Vivien Gornitz, Netherlands: Springer, 780–783.
Follmi, K.B. 1996. "The phosphorus cycle, phosphogenesis and marine phosphate-rich deposits" Earth Science Reviews 40: 55–124.
Guidry, M.W., Mackenzie, F.T., and Arvidson, R.S. 2000. "Role of tectonics in phosphorus distribution and cycling". In Marine Authigenesis, edited by C.R. Glenn L., Prevot-Lucas and J Lucas. Global Microbial. Spec. publ. #66 SEPM, 35–51.
Gunther, F. 1997. "Hampered effluent accumulation process: phosphorus management and societal structure." Ecological Economics 21: 159–174.
Herbert, D.A. and Fownes, J.H. 1995. "Phosphorus limitation of forest leaf area and net primary productivity on a weathered tropical soil". Biogeochemistry 29: 223–225.
Howard, P.F. 1979. "Phosphate." Economic geology 74: 192–194.
Hyland, C. Ketterings, Q., Dewing, D., Stockin, K., Czymmek, K., Albrecht, G. and Geohring, A. 2005. "Phosphorus Basics-the phosphorus cycle." Factsheet No. 12, Cornell University Cooperative Extension, Nutrient management spear programme.
Indian Minerals Yearbook, Part III. 2015. "Mineral Reviews, Apatite and Rock Phosphate." Nagpur, Indian Bureau of Mines, Ministry of Mines.
Jahnke, R.A. 2000. "The Phosphorus cycle". In Earth System Science; From Biogeochemical cycles to global climate change. Academic Press limited , 360–376.
Martens, W.J.M. and Rotmans, J. 1999. "The Global phosphorus cycle." In Climate change: an integrated perspective. 122–125

Mortvedt, John J. and Beaton, J. D. 1996. "Heavy metal and radionuclide component in phosphate fertilizers." In Phosphorus in Global environment: Transfers, cycles and management, SCOPE 54, John Wiley and Sons.
Nezat, C.A., Blum, J.D., Yanai, R.D., and Hamburg, S.P. 2007. "A sequential extraction to determine the distribution of apatite in granitoid soil mineral pools with application to weathering at the Hubbard Brook experimental forest, NH USA". Applied Geochemistry 22 no.1: 2406–2421.
Nriagu, J.O., and Moore, P.B. 1984. Phosphate Minerals. New York: Springer-Verlag.
Parfitt, R.L., Ross, D.J., Coomes, D.A., Richardson, S.J., Smale, M.C. and Dahlgren, R.A. 2005. "N and P in New Zealand soil chronosequence and relationship with foliar N and P". Biogeochemistry 75: 305–328.
Redfield, A.C., Smith, H.P. and Ketchum, B. 1963. "The influence of organisms on the composition of sea water". In The Sea, edited by M.N. Hill. New York: Interscience, 26–77.
Richardson, J.E. and Simpson R.J. 2011. "Soil microorganisms mediating phosphorus availability" Plant Physiology 156: 989–996.
Ruttenberg, K.C. 2008. "Phosphorus Cycle". In Encyclopaedia of Global Change. Oxford
Ruttenberg, K.C. 2007. "The Global Phosphorus Cycle: Overview". In The Treatise on Geochemistry Volume 8 Elsevier, 585–643.
Schimel, D.S. et al. 1994. "Climate, edaphic and biotic controls over carbon and turnover of carbon in soils". Global Biogeochemical Cycles 8: 279–293.
Schindler, D.W. 1977. "Evolution of phosphorus limitation in lakes". Science 195: 260–262.
Slansky, M. 1980. "Geology of the Sedimentary Phosphates" in (North Oxford Academic 1980), 12–16.
Smil, V. 2000a. "Feeding the world: A Challenge for the 21st century". Cambridge: The MIT Press.
Smil, V. 2000b. "Phosphorus in the environment: natural flows and human interferences". Annual Review of the Energy and the Environment 25: 53–88.

Smil, V. 2002. “Phosphorus: global transfers”. In Encyclopaedia of Global Environmental Change, edited by P.I. Douglas. Chichester: John Wiley and Sons.
Soon, Y.K. 2008. “Phosphorus Cycle”. In Encyclopedia of Soil Science (Encyclopedia of earth science series). Edited by Ward Chesworth. Netherlands: Springer, 547–555.
Srivastava, P., Kumar, A., Mishra, A., Meena, N.K., Tripahti, J.K., Sundriyal, Y.P., Agnihotri, R., Gupta, A.K. 2013. “Early Holocene monsoonal fluctuations in the Garhwal higher Himalaya as inferred from multi-proxy data from the Malari paleolake”. Quaternary Research 80, no.3: 447–458.
Steen, I. 1998. “Phosphorus availability in the 21st Century: management of a non-renewable resource”. Phosphorus and Potassium 217: 25–31.
Stevens, P.R. & Walker, T.W. 1970. “The chronosequence concept and soil formation”. The Quarterly Review of Biology 45, no. 4: 333–350.
Straaten, P. 2008. “Phosphorus”. In Encyclopedia of Soil Science (Encyclopedia of earth science series). Edited by Ward Chesworth. Netherlands: Springer, 241–247.
UN, Millennium Development Goals Report. 2005. New York, Department of Economic and Social Affairs of the United Nations Secretariat.
USGS. 2008. “Mineral commodities summaries”. Digital data series, DDS-37. US Geological Survey 2008. http://minerals.usgs.gov/minerals/pubs/mcs/
Vuuren, D.P., Van, Bouwman, A.F., and Beusen, A.H.W. 2010. “Phosphorus demand for the 1970-2100 period: A scenario analysis of resource depletion”. Global Environmental Change 20: 428–439.
Walker, T.W. and Syers, J.K. 1976. “The fate of phosphorus during pedogenesis”. Geoderma 15: 1–19.
World Bank. Accessed on 9 March 2016 http://data.worldbank.org/indicator/AG.CON.FERT.ZS/countries/
Zapata, F., and Roy, R. 2012. “Use of phosphate rocks for sustainable agriculture”. Food and Agriculture Organization of the United Nations. Accessed 25 November 2012. http://www.fao.org/docrep/007/y5053e/y5053e07.htm#bm07.