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Underappreciated Resource Phosphorus : Implications in Agronomy

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Phosphorus (P) which is required by all living plants and animals is an important input for economic crop and livestock production systems. Phosphorus containing compounds are essential for photosynthesis in plants, for energy transformations and for the activity of some hormones in both plants and animals. Loss of soil P to water can occur in particulate forms of P with eroded surface soil and in soluble forms in runoff, soil interflow, and deep leaching. The excessive losses of P from agricultural systems can degrade water quality of surface waters, resulting in accelerating eutrophication. Thus, P is often the limiting element and its control is of prime importance in reducing the accelerated eutrophication of surface waters. However, reserves of phosphate begin to run out, the impacts are likely be immense in terms of rising food prices, growing food insecurity. This paper reviews underappreciated resource as a key component of fertilizers and one of controversial pollutant in terms agronomy and environment.

Key words: Phosphorus, Pollutant, Nutrient, Agronomy, Environment

Introduction

Mining phosphorus for fertilizer is consuming the mineral faster than geologic cycles can replenish it. The world's diminishing mineral resources that have received much less attention are easy to come by. The world has enough potassium to last several centuries. But phosphorus is a different story. In August of 2009, the Broker reported that reserves of phosphate rock, the main source of phosphorus used in fertilizers, are running out. Also Vaccari (2009) reminded that we must act now to conserve it, or future agriculture could collapse.

Phosphorus (P), an essential element for plant growth, is a naturally occurring element that can be found in the earth'crust, water, and all living organisms. In areas of intensive crop and livestock production, continual P applications as mineral fertilizer and manure have been made at levels exceeding crop uptake (Sharpley et al., 1994; Wikipedia, 2010a). As a result, accumulations of P in soil surface have occurred to such an extent that the continued application of P to agricultural land and its subsequent movement to surface waters in runoff have become a priority management concern due to the increased growth of undesirable algae and aquatic weeds.

Phosphorus together with nitrogen and potassium is one of the three key components of fertilizers. We obtain nitrogen from the air, but we must mine phosphorus and potassium (USGS. 2010). In the 20th century the three nutrients enabled agriculture to increase its productivity and the world's population to grow more than sixfold. Both sources expect that readily available global supplies may start running out by the end of this century while by then our population may have reached a peak that some say is beyond what the planet can sustainably feed. In terms of rising food prices, growing food insecurity and widening inequalities among countries, the impacts are likely be immense as reserves of phosphate begin to run out.

So far there has been little acknowledgement from governments, researchers, private sector or domestic NGOs to the world' dwindling phosphate reserves. Yet articles are not beginning to appear highlighting the implications of the situation of P supplies in Korea which relies most of all natural resources on foreign countries. In this article, we briefly reviewed phosphorous in terms of agronomic and environmental aspects with intent to improve public awareness of the problem related to phosphorous.

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Peak Phosphorus

What does Peak Phosphorus mean? Our ability to provide enough food to feed the human population is dependent on the availability of phosphorus. While the term "peak oil" has become a familiar term in the lexicon of sustainability, the notion of "peak phosphorus" may ultimately be a concern of greater consequence.

All over the world farmers treat their fields with phosphorus-rich fertilizer to increase the yield of their crops. What happens next, however, receives relatively little attention. Dwindling supply of phosphorus, a primary component underlying the growth of global agricultural production, threatens to disrupt food security across the planet during the coming century (Wikipedia. 2010b).

The world's reliance on phosphorus is an unappreciated aspect of the "Green Revolution," a series of agricultural innovations that made it possible to feed the approximately 4.2 billion-person increase in the global population since 1950.

The supply of mined phosphorus is running out. Global demand for fertilizers led to large increase in phosphate (PO_4^{3-}) production in the second half of the 20th century. Some initial analyses from scientists with the Global Phosphorus Research Initiative (2010) estimate that there will not be sufficient phosphorus supplies from mining to meet agricultural demand within 30 to 40 years (Elser and White, 2010). Lewis (2008) stated that the supply of phosphorus at the current rate of consumption was estimated to run out in 345 years. However, New Scientist (2010) and Vaccari (2010) mentioned that scientists are now claiming that a "Peak Phosphorus" will occur in 30 years and that reserves will be depleted in the next 50 to 100 years at current rates,

Nearly 90 percent of the world's estimated phosphorus reserves are found in five countries: Morocco, China, South Africa, Jordan, and the United States. Reflecting these concerns, U.N.-sanctioned export restrictions on phosphate and other resources are now in place, though the efficacy of the bans is incomplete. China, the country with the largest phosphorus reserves after Morocco, imposed a 135 percent tariff on the resource as part of 2008's complex series of events in which rising fuel and fertilizer costs led to rapid increases in food prices (Rosemarin et al., 2009)

Establishing a reliable phosphorus supply is essential for assuring long-term, sustainable food security. If we fail to meet this challenge, humanity may face a Malthusian trap of widespread famine on a scale that we have not yet experienced. If we are successful in rising to the phosphorus sustainability challenge, as well as other aspects of sustainable agriculture, we can look forward to a future in which families, communities, and countries are healthy and secure in their nutrition.

What is phosphorous? Phosphorus was first obtained from bone ash, and from the mid-1800s from rock phosphate, or apatite, which is found in fossil marine sediments and volcanic deposits.

Phosphorus which was discovered in 1669 by Hennig Brand is the chemical element that has the symbol P and atomic number 15. Phosphorus as a mineral is almost always present in its maximally oxidized state, as inorganic phosphate rocks. Phosphorus has several forms (allotropes) that have strikingly different properties. (Holleman and Wiberg, 1985). The two most common allotropes are white phosphorus and red phosphorus. Red phosphorus is an intermediate phase between white and

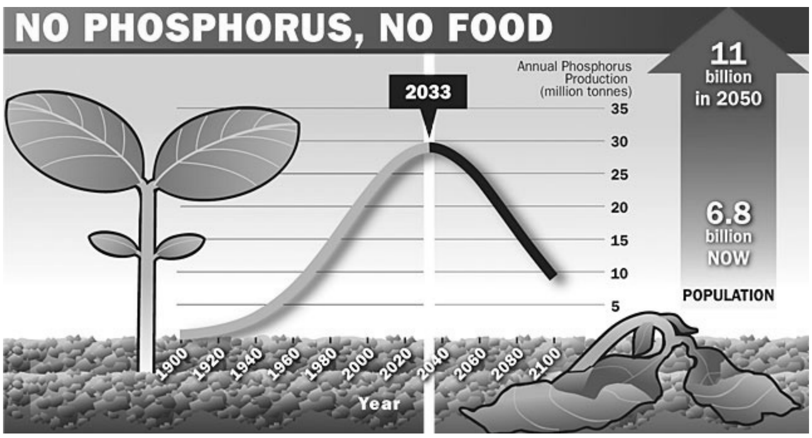

Fig. 1. Peak phosphorus.

violet phosphorus. Another form, scarlet phosphorus, is obtained by allowing a solution of white phosphorus in carbon disulfide to evaporate in sunlight. Black phosphorus is obtained by heating white phosphorus under high pressures. Another allotrope is diphosphorus; it contains a phosphorus dimer as a structural unit and is highly reactive (Berger, 1996). Due to its reactivity with air and many other oxygen-containing substances, phosphorus is not found free in nature but it is widely distributed in many different minerals.

Phosphate rock, which is partially made of apatite (an impure tri-calcium phosphate mineral), is an important commercial source of this element. About 50 percent of the global phosphorus reserves are in the Arab nations. (USGS, 2009) Large deposits of apatite are located in China, Russia, Morocco, Florida, Idaho, Tennessee, Utah, and elsewhere.

Terrestrial Phosphorus Cycle

The global phosphorus cycle has four major components : (1) tectonic uplift and exposure of phosphorus-bearing rocks to the forces of weathering; (2) physical erosion and chemical weathering of rocks, producing soils and providing dissolved and particulate phosphorus to rivers; (3) riverine transport of phosphorus to lakes and the ocean; and (4) sedimentation of phosphorus associated with organic and mineral matter that is buried in aquatic sediments (Jahnke, 1992).

As shown in Fig. 2, phosphorus can be found on earth only in water, soil and sediments. It is mainly cycling through water, soil and sediments. Phosphorus moves slowly from deposits on land and in sediments, to living organisms, and than much more slowly back into the soil and water sediment. Phosphorus is most commonly found in rock formations and ocean sediments as phosphate salts which are released from rocks through weathering usually dissolve in soil water and will be absorbed by plants. Phosphorus cycles through plants and animals much faster than it does through rocks and sediments. When animals and plants die, phosphates will return to the soils or oceans

Table 1. Properties of some allotropes of phosphorus.

Form	white (α)	white (β)	violet	black
Symmetry	Body-centred cubic	Triclinic	Monoclinic	Orthorhombic
Pearson symbol		aP24	mP84	oS8
Space group	I43m	P1 No.2	P2/c No.13	Cmca No.64
Density (g cm^{-3})	1.828	1.88	2.36	2.69
Bandgap (eV)	2.1		1.5	0.34
Refractive index	1.8244		2.6	2.4

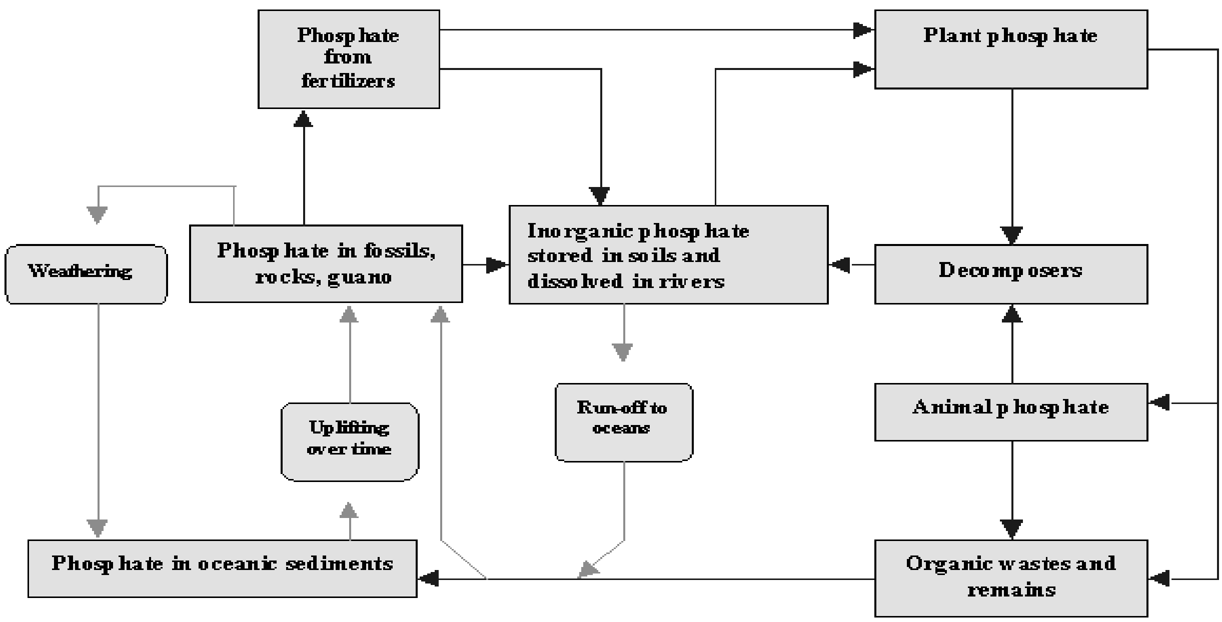

Fig. 2. A schematic representation of the phosphorus cycle.

again during decay. After that, phosphorus will end up in sediments or rock formations again, remaining there for millions of years. Eventually, phosphorus is released again through weathering and the cycle starts over.

In terrestrial systems, phosphorus resides in three pools: bedrock, soil, and living organisms (biomass). Phosphorus, weathered from bedrock by the dissolution of phosphorus-bearing minerals such as apatite ($Ca_{10}[PO_4]_6[OH,F,Cl]_2$), is available for uptake by terrestrial plants and is returned to the soil by the decay of dead plant material (Tiessen, 1995).

P is generally recycled to various extents in ecosystems depending on climate, soil type, and ecosystem level. The release of P from apatite dissolution is a key control on ecosystem productivity (Cole et al. 1977, Tiessen et al. 1984, Roberts et al. 1985, Crews et al. 1995, Vitousek et al. 1997, Schlesinger et al. 1998). Furthermore, the weathering of P from the terrestrial system and transport by rivers is the only appreciable source of P to the oceans. Systematic changes in the total amount and chemical form of phosphorus occur during soil development. In initial stages, phosphorus is present mainly as primary minerals such as apatite. In midstage soils, less soluble secondary minerals and organic phosphorus make up an increasing fraction of soil phosphorus as the reservoir of primary apatite is diminished. In highly weathered soils as the latest stage of soil development, phosphorus is partitioned mainly between refractory minerals and organic phosphorus. Based on these soil development stages Filippelli (1999) presented an overview of the natural (pre-human) and modern (syn-human) global P mass balances as the global phosphorus cycle.

Natural (pre-human) phosphorus cycle is that the initial source of P to the global system is released mainly from apatite minerals via the weathering of P during soil development. But the physical weathering which plays in producing fine materials with extremely high surface area/mass ratios results in P that is typically unavailable to biota (Filippelli, 1999).

Modern (syn-human) phosphorus cycle is substantially different from the natural (pre-human) phosphorus cycle. The net increase in dissolved-P release from land due to human activities also includes deforestation (plus concurrent soil loss), sewage, and waste sources. Sewage and waste are additional anthropogenic contributors to the terrestrial P cycle. This P is rapidly leached from the ash and transported as dissolved loads in rivers; this transfer can happen on timescales of a year or two (Schlesinger 1997).

The Soil Phosphorus Cycle In most soils, the P content of surface horizons is greater than that of subsoil due to the adsorption of added P and greater biological activity and accumulation of organic material in surface layers. However, soil P content varies with parent material, texture, and management factors, such as the rate and type of P applied and soil cultivation. These factors also influence the relative amounts of inorganic and organic P.

The complex nature of the chemical and microbiological reactions that control phosphorus availability in agricultural systems is illustrated in the soil phosphorus cycle (Fig. 3). Phosphorus in soils originates from the weathering of residual minerals and from phosphorus additions in the form of fertilizers, plant residues, agricultural wastes and/or biosolids. The type of phosphorus bearing minerals that form in soil is highly dependent on soil pH. Phosphorus reacts with iron (Fe) and aluminum (Al) to form insoluble Fe and Al phosphates in acid soils and with

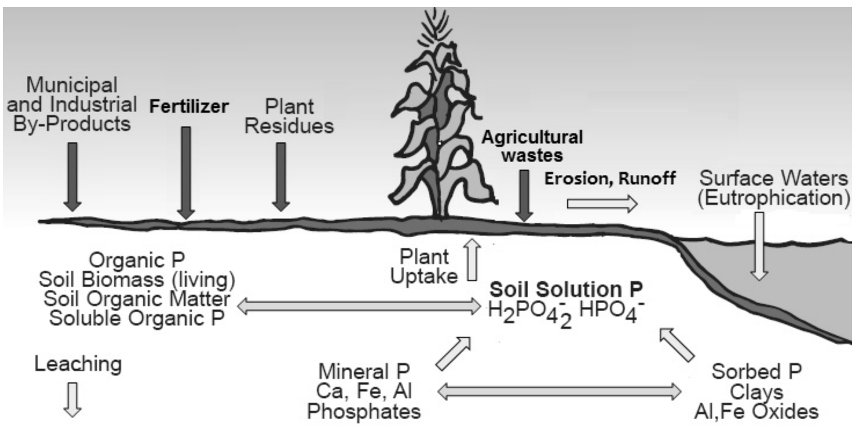

Fig. 3. The soil phosphorus cycle (adapted from Pierzynski et al., 1994).

calcium (Ca) to form insoluble Ca phosphates in alkaline soils.

The release of soil phosphorus to plant roots and its potential movement to surface waters is controlled by several chemical and biological processes. Phosphorus is released to the soil solution as phosphorus-bearing minerals dissolve, as phosphorus bound to the surface of soil minerals is uncoupled (desorbed), and as soil organic matter decomposes (mineralizes). Most of the phosphorus added to soil as fertilizer and manure is rapidly bound by the soil minerals in chemical forms that are not subject to rapid release; thus, soil solution phosphorus concentrations are typically very low.

Phosphorus in agriculture

Phosphorus, one of the key essential elements in modern agriculture, finds its major use as a constituent of fertilizers for agriculture and farm production in the form of concentrated phosphoric acids, which can consist of 70% to 75% P_2O_5. Fertilization of crops comprises the largest proportion of P used in agriculture. Phosphorous use has become increasingly prevalent during recent decades due to its depletion in soils used for crop and hay production. The importance of P to crop production systems is illustrated by the amount of fertilizer-P used during the last 35 years, which has doubled since 1960, stabilizing at slightly under two million tons per year over the last 10 years.

In the plant, phosphorus is essential for a number of physiological functions that are involved with energy transformations. Phosphorus is a component of many cell constituents and plays a major role in several key processes, including photosynthesis, respiration, energy storage and transfer, cell division, and cell enlargement. Adequate phosphorus is needed for the promotion of early root formation and growth. Phosphorus also improves crop quality and is necessary for seed formation. Livestock also require phosphorus for proper growth. In addition to other functions, phosphorus is an essential component of bones and teeth. Animals derive their phosphorus needs from plant products and feed supplements.

Although the benefits of P on agricultural production are evident, this element can be a pollutant if it moves from the site. The main concern is P transport from soils to streams, rivers, lakes, and eventually oceans. Phosphorus transported from agricultural soils can promote eutrophication, which is enrichment with nutrients that leads to increased algal growth, and decreased dissolved oxygen.

Summary

Phosphorus as a non-renewable resource is not widely discussed. However, it is arguably one of the most important chemicals for the continued existence of life on planet Earth. Phosphate extraction will peak around 2030. So far we have failed to acknowledge the problem. Every effort should be made to recover and recycle phosphates whenever possible. Innovative strategies are urgently needed, especially agricultural reforms to reduce the demand for fertilizers, and policies to promote the recovery and reuse of phosphorus from organic waste. Therefore, we need to understand what forms of P occur in soils, the dynamics of cycling between forms of differing bioavailability (i.e., available for uptake by plants and aquatic biota) before we can develop environmentally sound agricultural systems for P.

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