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Phosphorus Scarcity

The dawn of agriculture began a new and exciting chapter in the human story. Through crop cultivation and domestication humanity freed itself from time consuming transhumance and put down roots. These revolutionaries were able to eat well all through the year by growing more than their immediate needs demanded and storing this bounty as surplus. With a surplus of food Neolithic peoples found themselves in possession of an even greater surplus: a surplus of time. They now had time to observe, time to tinker, and time to think. Villages formed, trades were invented, and ideas were explored. Agriculture provided the foundation for civilization.

Civilization today is as dependent as ever on agriculture. Our massive urban landscapes, and the tertiary and quaternary industries they support, would not be possible without the importation of nutrients from far distant fields. With over seven billion hungry humans on the planet those fields must produce more and more food with each passing season.

This modern industrial agriculture is able to meet the demand for high output through the use of a few key inputs: fossil fuels to power the machinery we now use in place of draft animals, pesticides to mitigate losses to predation, freshwater for irrigation, and chemical fertilizers to artificially improve soil fecundity. Aside from pesticides these key inputs are becoming dangerously scarce.

As we head into the endgame of resource scarcity it is crucial to institute a new, sustainable agricultural model. This paper will focus primarily on phosphorus as an agricultural input and seek to answer the question: how must our agricultural model change in order to make phosphorus use sustainable?

A Finite Resource

Elemental phosphorus, or P, was first identified in 1674 by a German alchemist named Hennig Brand—who isolated it from human urine (“Phosphorus”). Phosphorus is an essential plant nutrient, one of the major three nutrients—the other two being nitrogen and potassium. DNA’s double helix is built on a scaffold of phosphorus; so as Vaclav Smil puts it “No life (including microbial life) is possible without [phosphorus]” (54). P is most frequently the major limiting factor in plant growth, due to its immobility in soils and the ease with which it becomes insoluble when interacting with other minerals in the soil (Devau 2163).

Current agricultural methods supply cultivated crops with an abundance of usable phosphorus by regular applications of phosphate fertilizer which we derive from the mining and refining of phosphate rock. These phosphate rock formations take 15 million years to form, rendering phosphate an effectively finite resource (Jasinski). Predictions for total depletion of our remaining reserves range from 50-150 years, while the Global Phosphorus Research Initiative (GPRI) predict the first major shortages will occur within thirty years’ time (Smil 81, Gunther, GPRI). Meanwhile we’re on track to bump the global human population to 9.2 billion by 2050 (Cribb 10). Our use of fossil energies, like phosphate rock, have allowed us to artificially inflate the effective carrying capacity of the earth, but when the phosphate fertilizers run out and crop yields crash it just means the number of people starving to death will be that much greater.

One factor that could contribute to the disruptions predicted by the GPRI may be the lopsided distribution of the world’s reserves. Of what little phosphate rock remains 83% is concentrated in just one relatively small region: Western Sahara (Jasinksi 119). Western Sahara is probably better known for its status as the last colony of Africa than for its massive phosphorus reserves--until 1975 Western Sahara was controlled by Spain, who administered the region as a colony. When Spain decamped, following the Madrid Agreement, Morocco occupied the region--claiming the phosphate rock reserves for its own. The native Sahwari people, however, dispute this claim and while the conflict is presently non-violent it is, as yet unresolved (CIA 704). The majority of the world's remaining reserves, therefore, are located in a politically turbulent area and should civil war begin in earnest the global supply—and by extension the global harvest--would likely be disrupted.

A Linear System

It is not the rarity of phosphate rock which has ultimately led us to our current perch on the brink of famine; but the failure to address those obstacles in the agricultural system which are inherent to civilization. Civilization, as Derrick Jensen points out in his book "Endgame," is a "culture that both leads to and emerges from the growth of cities" (Jensen 17). Jensen goes on to define cities, at the most basic level, to be "people living permanently in one place, in high enough densities to necessitate the routine importation of food and other resources." This importation of food is a linear movement of nutrients from distant agricultural soils to urban centers where they are concentrated, and from there are released into the greater environment as waste; ultimately ending up either in the oceans or interred in landfills. This one way nutrient flow is the primary reason agricultural soils depend on regular applications of phosphate rock fertilizer. The short-sighted, linear design of our industrial agricultural system has amplified phosphorus scarcity to a global threat to food security and population maintenance. We have inherited an inefficient system that separates production, consumption, and waste.

A simplified, but useful way of looking at the current system of phosphorus movement is to imagine it as a leaky pipeline. The mouth of the major pipes are large at their sources—the mines. They narrow and split all the while leaking wastefully as the bulk is carried to the production fields of the world. From each field is another pipe representing the waste from over-application that's transferred to surface waters and eventually finds its way to the oceans. In nature the phosphorus within the bodies of plants would decompose on site to enrich the soil for the next generation, but as Dana Cordell summarizes: "Unlike the natural biochemical cycle, which recycles phosphorus back to the soil 'in situ' via dead plant matter, modern agriculture harvests crops prior to their decay phase, transporting them all over the world to food manufacturers and to consumers" (Cordell 295). So there is another smaller pipe from each field which leads to the cities and towns of the world. Phosphorus moves down these pipes in the form of food. It enters the city, is eaten and the remaining phosphorus enters yet another pipe; a sewage pipe that empties into the ocean. One could be forgiven for viewing industrial agriculture as nothing more than a Rube Goldberg device for moving phosphorus from the land to the sea. We need to employ an army of plumbers to patch the leaky pipes and reroute the works so the line terminates back in the fields rather than the world's oceans.

The greatest point of waste of phosphorus in the industrial agriculture system is at the point of field application. According to Paul Brunner, who applied system flow analysis to anthropogenic phosphorus movement: "10 units of P input result in only one unit of P utility (food)" (871). So where does the unused P go? Nutrient retention by soils, surface water transfer, and sub-soil penetration are all site-specific and so there is a deal of regional variance, but on average 25% is transferred to surface waters--either directly by solubilization, or through soil erosion--and the remaining phosphorus is retained on-site (Rosemarin 31, Brunner 871).

So if around seventy-five percent of applied phosphorus is retained on site it begs the question why must we apply phosphorus fertilizer annually? The answer is that phosphorus is easily fixed in insoluble forms in the soil—making it unavailable to plants. According to the University of Minnesota's Agricultural Extension:

> The fixed-P pool of phosphate will contain inorganic phosphate compounds that are very insoluble and organic compounds that are resistant to mineralization by microorganisms in the soil. Phosphate in this pool may remain in soils for years without being made available to plants and may have very little impact on the fertility of a soil. (Busman).

A portion of the P in this pool of fixed phosphate can become available in a form useful to plants through various weathering mechanisms, most notably by the actions of mycorrhizal fungi, but the majority will be fixed in fine soil particles (Busman). Understanding these aspects of phosphorus fixation in agricultural soils leads to a further understanding of the means by which modern practices amplify phosphorus losses.

Modern farming practices revolve around fossil fuel powered machinery. It takes machinery to sow the seed and to harvest the crop. Machinery is incredibly heavy. As combines zigzag through a field collecting those precious ears of corn they also compact the soil. This means come spring more heavy machinery will be needed to plow and harrow the fields to release this compaction. This destroys the incredibly vast, delicate systems of arbuscular mycorrhizal hyphae which serve to mobilize otherwise insoluble phosphorus to the roots of crop plants as well as contribute to soil stabilization (Duan et al 270). This mechanical interference with natural soil structure results in soils that easily erode—particularly through rainfall inundation and flood irrigation. When water permeates and moves through soil it tends to be the smallest particles that are washed out and deposited in surface water. These are the same small particles where phosphorus is most likely to concentrate during soil fixation (Busman).

This seasonal loss combined with fertilizer subsidies that many countries offer and which artificially lower the cost of these inputs result in an over-application of phosphorus which is criminally inefficient. Dana Cordell, however, suggests it is this very inefficiency that provides optimism for a sustainable future. “Phosphorus is lost,” she says, “at all key stages of the food system, from mine to field to fork, meaning there are substantial opportunities for improving efficient use and reuse” (“Phosphorus Security” 747).

A sustainable agriculture would best address this nutrient loss through no-till farming and surface water slowing achieved through on-contour swaling. No-till farming has been shown to reduce soil erosion—mitigating phosphorus loss (Roberson 7). In no-till farming soil structure is preserved by planting directly into the stubble remaining from the previous harvest. In this way soil structure and health is maintained year round and losses to wind and water erosion are reduced to a minimum. Less water is needed for irrigating no-till fields, machinery use and associated fuel costs are likewise reduced, and since fewer nutrients are lost through surface water transfer the need for chemical fertilizer inputs is also reduced (Perry 19). No-till farming, therefore, can reduce the three most critical and finite inputs necessary for modern industrial agriculture: fossil fuels, fresh water, and chemical fertilizers. Reducing losses is one aspect of sustainability, another is recycling. There is a major avenue of loss where substantial phosphorus could be recovered. This is the same place Hennig Brand first found phosphorus: human excreta.

A Thin Line between Pollutant and Resource

Dana Cordell estimates the global human population excretes around 3 million tons of phosphorus in urine and feces annually (“Story of Phosphorus” 296). This excreta is currently viewed as waste, but the reality is it’s an incredible resource. There are a few municipalities, worldwide, endeavoring to reclaim nutrients from the human waste stream. In Sweden, Australia, and even my native Oregon several methods and policies have been implemented to address waste reduction and facilitate recycling. While motives may vary from an active desire to reduce phosphorus imports to a desire to protect coastal fisheries, the end result is a recycling of nutrients from the human waste stream.

Rather than as an inefficient waste of finite resources many countries approach the issue as a matter of simple pollution. Sweden, for instance, aggressively pursues polluters, holding upstream farmers responsible for downstream water quality under a polluter-pays model (Löwgren 501). Sweden has implemented and enforced what’s known as Extended Producer Responsibility (EPR) which is a pollution-reduction method suggested by the Organization for Economic Co-operation and Development, or OECD, which is a primarily European trade organization. EPR is defined by the OECD as

> a concept where manufacturers and importers of products should bear a significant degree of responsibility for the environmental impacts of their products throughout the product life-cycle, including upstream impacts inherent in the selection of materials for the products, impacts from manufacturers’ production process itself, and downstream impacts from the use and disposal of the products. Producers accept their responsibility when designing their products to minimise life-cycle environmental impacts, and when accepting legal, physical

> or socio-economic responsibility for environmental impacts that cannot be eliminated by design. (OECD)

Basically the cost of pollution, on all levels, are quantified and incorporated into the cost of the final product, so that producers are rewarded by market incentives to keep their environment impact low.

While Sweden’s approach is unique, similar policies do exist here in the United States. I interviewed Peter Schauer, the principal process engineer at the Durham waste treatment plant in Tigard, Oregon. The Durham treatment plant is one of the very first treatment facilities in the United States to actively recover phosphorus from the waste stream, in the form of struvite. The struvite is recovered through a proprietary process developed by the Canadian firm Ostara, and is marketed as a slow release phosphorus fertilizer under the brand name Crystal Green. During that interview Mr. Schauer informed me that the motive behind the implementation of struvite recovery had less to do with a desire to recover nutrients that would otherwise be lost but instead to stay in compliance with the EPA’s National Pollutant Discharge Elimination System (NPDES).

The Tualatin river, into which the Durham plant discharges its treated waste is a small river and even trace amounts of phosphorus in the effluent can cause massive algae blooms during the spring and summer months. These algae blooms occur due to eutrophication—an over-abundance of nutrients—and one of the metabolic side-effects of the rapid algae reproduction is a depletion of dissolved oxygen in the water. The phosphorus in this effluent can not only lead to freshwater eutrophication, but can also combine in coastal waters with nutrient laden runoff from other watersheds where the resulting harmful algae blooms can cause hypoxic areas or, as they’re more popularly known, dead zones (Solow 43). So while nutrient recovery is a useful byproduct of the process Mr. Schauer says “Our primary concern is to achieve a high treatment level without the need to use more chemicals while also reducing the environmental impact to the receiving stream” (Schauer). Despite the motivating mindset of curtailing pollutants to protect coastal and inland waters the net result is the same: a recovery of field ready nutrients that would otherwise have ended up lost to the ocean.

Tallying of Costs

Many who oppose major agricultural reform arrive at their opposition by starting from premises which suggest a narrow and compartmentalized view of the situation. For instance the most recent study to grab headlines was done by a team from McGill University in Montreal, Canada. This meta-analysis found that yields from organic farms were significantly lower than yields from industrial agriculture. The opposition often point out that soy and corn yields per hectare cultivated using sustainable methods do not achieve the higher yields industrial agriculture offers. I think it’s important to zoom out a little and assess the criteria used to measure yields per hectare. A one-step thinker may simply look at the acres under cultivation on an Iowa farm and compare that number to the product removed in one harvest. Indeed this seems to be the criteria to quantify production used by Seufert’s team . A multi-step thinker, however, may look beyond the crop weight of the area under cultivation and consider the weight of imported chemical fertilizers and the energies expended in their extraction, refinement, and transportation across the globe. A multi-step thinker might also look at the outflow and waste from the growing process—specifically the transfer of chemical fertilizers to surface waters, streams, rivers, and on to the ocean. From Iowa’s corn fields flow concentrated nutrients that make their way hundreds of miles down the Mississippi to the Gulf of Mexico. There those nutrients feed massive algae blooms which completely deplete the dissolved oxygen from the water causing massive die-off amongst marine life.

A multi-step thinker might erect a massive scale with the Iowa corn on one side and all the chemical and fuel inputs as well as the dead fish from the gulf on the other. The remainder, if any exists, can be counted as yield per hectare. A multi-step thinker would likely recognize when the accounting is complete and tallying done sustainable agriculture can and does result in much higher yields.

In the same realm of quantifying output it is certainly useful to quantify, monetarily, the nutrients lost post-consumption. A group of researchers from the University of Cincinnati did just that. The researchers conclude:

> In the US, approximately twenty thousand publicly owned treatment plants process more than thirty five billion gallons of sewage each day. The current cost of treatment is approximately twenty billion dollars per year. With an average phosphorus content of nearly 10 mg/liter, assuming phosphorus recovery of ninety percent and a retail value of struvite of $400 per ton, phosphorus recovery from wastewater represents an annual gross revenue of nearly*$3.5* billion dollars. (Oerther et al)

This doesn't even take into consideration the fiscal impact to coastal fisheries which have been diminished due to eutrophication. The cost of implementing recovery processes must also be taken into consideration. According to Ostara, the company who owns the patent on the struvite recovery processes the capital cost of implementing their technology comes to roughly $2.5

million per plant. This is a cost they anticipate will be recovered within five years from a combination of struvite revenues and operational cost savings of up to $500,000 per year.

We are beginning to see erratic market fluctuations as the world supply of phosphate rock dwindles. 2008 saw an unprecedented spike in Phosphate prices, more than quadrupling from the year on year baseline price (Cordell 756). According to a report from the USDA the contributing factors to the 2008 price spike were an unpredicted reduction in extraction, both domestic and foreign, and a sudden increase in demand from farmers in developing countries (Huang). This recent price spike in rock derived phosphates has brought attention to the emerging industry of struvite recovery. The western world is beginning to recognize the value of its own sewage, a valuable resource China has long esteemed. In China human leavings, colloquially known as “night soil,” have been used to fertilize fields for centuries—providing not just phosphorus but nitrogen and potassium as well. The time was when Chinese farmers would go to town with a cartload of rice from the countryside and return with a cartload of night soil from the city. This integration of production, consumption, and waste is the backbone of sustainable agriculture. In a post-peak phosphorus world it is also the best hope for ensuring everyone gets enough to eat.

Examining the modern food production system reveals many vulnerabilities and threats to global food security and chief among these is phosphorus scarcity in a linear system. While the world learns to live within its means we must begin building a new agricultural model now to ensure no one is lost during the transition.

A Few Necessary Changes

After researching this subject it seems there are a few key points in our existing agricultural model at which phosphorus scarcity can be addressed without changing our methods too radically. These points are over-application, losses to surface water, and reclamation pre-terminus.

Over-application is the easiest aspect to correct. There are a number of ways to achieve it, but the most obvious would be to incentivize frugality. One method would be to eliminate fertilizer subsidies in countries that have them. When the cost of the input increases to reflect its actual market value farmers would likely be more judicious in its application. Another method which can be applied concurrent with subsidy elimination is to implement and, most importantly, enforce polluter-pays policies, like those used in Sweden. This has a two-fold effect: the most obvious is providing an incentive to agricultural producers to ensure their nutrients stay on site the second effect is to pass the cost of compliance into the price of the product. This may seem counterintuitive if our goal is the ready availability of affordable foodstuffs, but I believe in the long run market forces would arise to reward those producers who pollute least and force compliance on those who pollute most.

Losses to surface water can be mitigated by simple applied design. As fossil fuels will also tend to increase in scarcity a transition to a sustainable planting and harvesting method that does not depend on heavy machinery is requisite. Without heavy machinery there is no need for annual tilling and harrowing of fields, which will result in soils that are more stable and less easily eroded. This will however necessitate a transition from a model that relies primarily on capital inputs and move to one that relies primarily on labor inputs. It will be a transition that sees the ascendancy of the field hand over the combine harvester. The elimination of mechanized planters and harvesters means more water can be slowed and locked up within the landscape through on-contour swaling, which will further reduce phosphorus loss to surface water.

The last key point is reclamation of phosphorus before it reaches the current terminus of the human food web. This will be accomplished by integrating struvite recovery processes into new and existing waste treatment plants. This promises not only to address phosphorus scarcity, but also to be a sustainable source of revenue for municipalities as this exciting new industry emerges and grows.

We can and must create a new agricultural model that reintegrates production, consumption, and waste if we are to adequately meet the challenges that lie at the intersection of phosphorus scarcity and 9 billion humans crying out in hunger. Through a combination of policy changes, systems design, and applied technologies I'm confident we can meet those challenges.

Works Cited

Brunner, Paul. "Substance Flow Analysis as a Decision Support Tool for Phosphorus Management." *Journal of Industrial Ecology* 14.6 (2010): 870-873. *Academic Search Premier*. Web. 7 Oct. 2012.

Busman, Lowell, John Lamb, Gyles Randall, George Rehm, and Michael Schmitt. "The Nature of Phosphorous in Soils."*The Nature of Phosphorous in Soils*. University of Minnesota Agricultural Extension, 29 July 2012. Web. 19 Nov. 2012. http://www.extension.umn.edu/distribution/cropsystems/dc6795.html

Childers, Daniel et al. "Sustainability Challenges of Phosphorus and Food: Solutions From Closing the Human Phosphorus Cycle." Bioscience 61.2 (2011): 117-124. Academic Search Premier. Web. 24 Nov. 2012.

CIA: The World Factbook. "Western Sahara." *CIA World Fact Book* (2010): 704. *MasterFILE Premier*. Web. 25 Oct. 2012.

Cordell, Dana, Jan-Olof Drangert, and Stuart White. "The Story of Phosphorus: Global Food Security and Food for Thought." *Global Environmental Change* 19.2 (2009): 292-305. *GreenFILE*. Web. 12 Oct. 2012.

Cordell, Dana, Arno Rosemarin, Jaap Schröder, and Albert Smit. "Towards Global Phosphorus Security: A Systems Framework for Phosphorus Recovery and Reuse Options." *Chemosphere* 84.6 (2011): 747-758. *Academic Source Premier*. Web. 7 Oct. 2012.

Cribb, Julian. *The Coming Famine: The Global Food Crisis and What We Can Do To Avoid It*. Berkeley, Calif.: University of California Press, 2010. Print.

Devau, Nicolas et al. "Soil Ph Controls The Environmental Availability of Phosphorus: Experimental and Mechanistic Modelling Approaches." Applied Geochemistry 24.11 (2009): 2163-2174. Academic Search Premier. Web. 16 Nov. 2012.

Duan, Tingyu et al. "New Agricultural Practices in the Loess Plateau of China do not Reduce Colonisation by Arbuscular Mycorrhizal or Root Invading Fungi and do not Carry a Yield Penalty." Plant & Soil 331.1/2 (2010): 265-275. Academic Search Premier. Web. 25 Nov. 2012.

GPRI, comp. "Global Phosphorus Fertilizer Consumption." Chart. *Global Phosphorus Network*. Global Phosphorus Research Initiative, 2010. Web. 25 Oct. 2012. <http://globalpnetwork.net/facts-figures?>.

Gunther, F., 2005. “A Solution to the Heap Problem: The Doubly Balanced Agriculture: Integration with Population.” Available: http://www.holon.se/folke/kurs/Distans/Ekofys/Recirk/Eng/balanced.shtml.

Huang, Wen-Yuan. "Factors Contributing to the Recent Increase in U.S. Fertilizer Prices, 2002-08 / Wen-Yuan Huang." n.p.: [Washington, D.C.] : U.S. Dept. of Agriculture, Economic Research Service, [2009], 2009. Agricola. Web. 7 Dec. 2012.

Jasinksi, Stephen M, ed. "Phosphate Rock Statistics and Information." *USGS Minerals Information: Phosphate Rock*.” United States Geological Survey, 24 Oct. 2012. Web. 26 Oct. 2012. <http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/>.

Jensen, Derrick. *Endgame*. New York: Seven Stories, 2006. Print.

Linderholm, Kersti, Anne-Marie Tillman, and Jan Erik Mattsson. "Life Cycle Assessment Of Phosphorus Alternatives For Swedish Agriculture." Resources, Conservation & Recycling 66.(2012): 27-39. GreenFILE. Web. 25 Nov. 2012.

Liu, Yi, Gara Villalba, Robert Ayres, and Hans Schroder. "Global Phosphorus Flows and Environmental Impacts from a Consumption Perspective." *Journal of Industrial Ecology* 12.2 (2008): 229-247. *Academic Search Premier*. Web. 12 Oct. 2012.

Löwgren, Marianne. "The Water Framework Directive: Stakeholder Preferences and Catchment Management Strategies-are they Reconcilable?" *Ambio* 34.7 (2005): 501-6. *ProQuest*

Biology Journals. Web. 25 Nov. 2012.

Lougheed, Tim. "Phosphorus Paradox: Scarcity and Overabundance of a Key Nutrient." *Environmental Health Perspectives* 119.5 (2011): A209-A213. *Academic Search Premier*. Web. 7 Oct. 2012.

OECD. "Resource Productivity and Waste." *Resource Productivity and Waste*. Organisation for Economic Co-operation and Development, 2006. Web. 07 Dec. 2012.

Oerther, Daniel, et al. "Phosphorus Recovery from Sewage." *Epa.gov*. United States Environmental Protection Agency, 15 Nov. 2005. Web. 26 Oct. 2012. <http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/7345/report/F>.

Ostara. *Durham Treatment Facility First in the U.S. to Recycle Nutrients Into Green Commercial Fertilizer*. *Clean Water Services*. Clean Water Services, 10 June 2009. Web. 08 Nov. 2012.

Perry, Ann. "No-Till Crops Can Improve Air Quality in the Pacific Northwest." Agricultural Research 60.6 (2012): 19. Business Source Premier. Web. 6 Dec. 2012.

"Phosphorus." Columbia Electronic Encyclopedia, 6Th Edition (2011): 1. Academic Search Premier. Web. 24 Nov. 2012.

Roberson, Roy. "No-Till Successful For North Carolina Cotton Growers." Southwest Farm Press 35.1 (2008): 6. MasterFILE Premier. Web. 6 Dec. 2012.

Rosemarin, Arno. "The Precarious Geopolitics of Phosphorus." Down to Earth: Science and *Environment Fortnightly* (2004): 27-34. *Sustainable Sanitation Alliance*. Sustainable Sanitation Alliance, 30 June 2004. Web. 19 Nov. 2012.

Ruttan, Vernon W. "Productivity Growth): 161-184. Business Source Premier. Web. 9 Nov. 2012.

Schauer, Paul. E-mail interview. 12 Nov. 2012.

Schröder, Jaap, Albert Smit, Dana Cordell, and Arno Rosemarin. "Improved Phosphorus Use Efficiency in Agriculture: A Key Requirement for its Sustainable Use." *Chemosphere* 84.6 (2011): 822-831. *Academic Source Premiere*. Web. 7 Oct. 2012

Smil, Vaclav. "Phosphorus in the environment: Natural Flows And Human Interferences." Annual Review Of Energy & The Environment 25.1 (2000): 53. Academic Search Premier. Web. 9 Nov. 2012.

Solow, Andrew R. "Red Tides And Dead Zones." Oceanus 43.1 (2004): 43-45. Academic Search Premier. Web. 25 Nov. 2012.