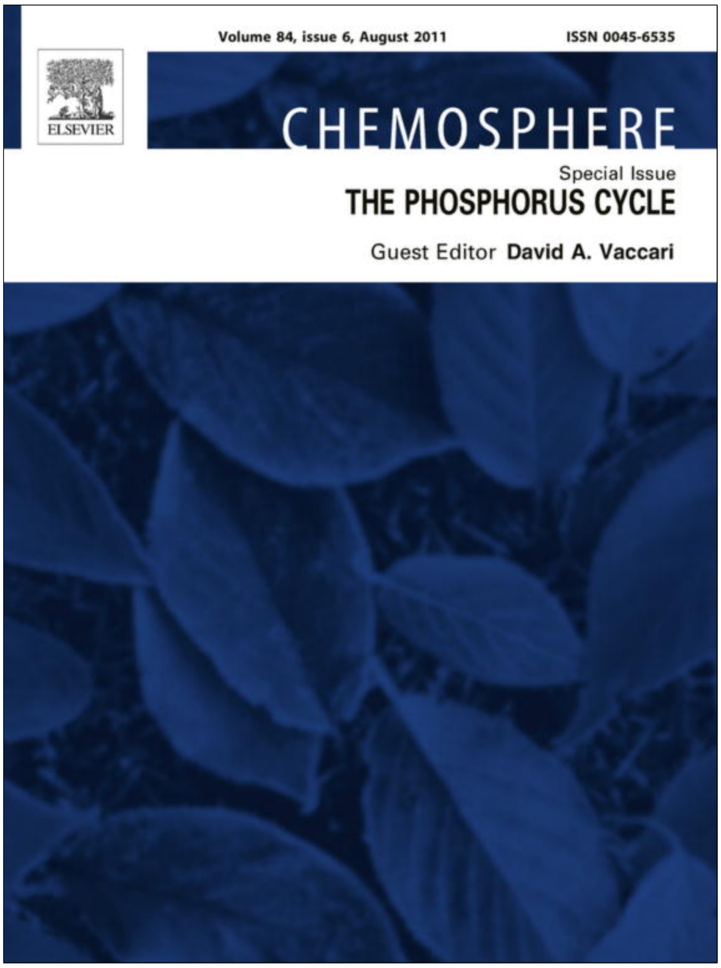
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A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse

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ABSTRACT

The element phosphorus has no substitute in sustaining all life and food production on our planet. Yet today's phosphorus use patterns have resulted in both a global environmental epidemic of eutrophication and led to a situation where the future availability of the world's main sources of phosphorus is uncertain. This paper examines the important history of human interference with the phosphorus cycle from initial discovery to present, highlighting key interrelated events and consequences of the Industrial Revolution, Sanitation Revolution and Green Revolution. Whilst these events led to profound advances in technology, public health and food production, they have fundamentally broken the global phosphorus cycle. It is clear a 'Fourth Revolution' is required to resolve this dilemma and ensure humanity can continue to feed itself into the future while protecting environmental and human health.

1. Introduction

The prominent chemist and science writer Isaac Asimov succinctly stated: "*Life can multiply until all the phosphorus has gone and then there is an inexorable halt which nothing can prevent*" (1974). The element phosphorus is essential to all life – plants, animals and bacteria. This means phosphorus has no substitute in growing crops and hence in food production. Yet, today's phosphorus use patterns in the global food production and consumption system have resulted in a global environmental epidemic of freshwater eutrophication and marine 'dead zones' (World Resources Institute, 2008) and simultaneously led to a situation where the future availability of the world's main sources of phosphorus are uncertain (Cordell et al., 2009).

Understanding the history of human-based phosphorus use can shed light on how we arrived at this unsustainable situation today, and assist in developing innovative solutions for future sustainable use of phosphorus. The story of phosphorus began with the alchemists search for the Philosopher's Stone, and centuries later, the critical role of phosphorus in soil fertility and crop growth was highlighted. Eventually, phosphorus was identified in the global environmental problem of eutrophication. Now, we are on the brink of yet another emerging chapter in the story: global phosphorus scarcity linked to food security (Fig. 1). This paper examines the important history of human interference with the phosphorus cycle from initial discovery to present, highlighting key interrelated events and consequences of the Industrial Revolution, Sanitation Revolution and Green Revolution.

2. The elemental discovery of phosphorus

Phosphorus has been a defining element throughout modern human history. The elemental form was discovered around 1669 by the German alchemist Hennig Brandt. Earlier origins are a mystery, as phosphorus may have been discovered in ancient Rome, then its secret lost through the ages (Emsley, 2000). In his Hamburg laboratory, Brandt distilled 50 buckets of urine through intense heating and distillation in search of the legendary 'Philosopher's Stone' that would supposedly turn base metals into gold (Emsley, 2000). His recipe was simple, yet effective (Ogilvy, 2006):

- *Boil urine to reduce it to a thick syrup.*
- *Heat until a red oil distills up from it, and draw that off.*
- *Allow the remainder to cool, where it consists of a black spongy upper part and a salty lower part.*
- *Discard the salt, mix the red oil back into the black material.*
- *Heat that mixture strongly for* 16 h.
- *First white fumes come off, then an oil, then phosphorus.*
- *The phosphorus may be passed into cold water to solidify.*

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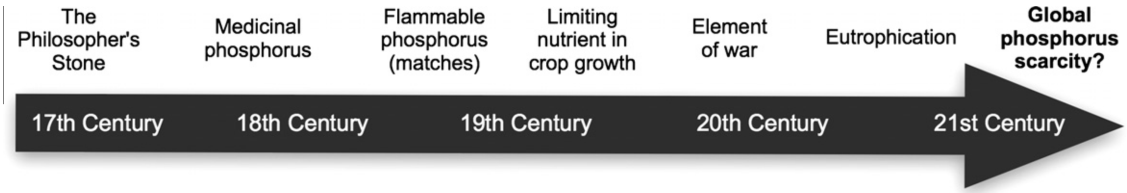

Fig. 1. The evolution of phosphorus use and abuse: from the Philosopher's Stone to use in war, food production, and more recently implicated in water pollution. A new emerging discourse of the 21st century may be global phosphorus scarcity. *Source*: Cordell (2010).

Whilst he found no such magical stone capable of transmutation, Herr Doktor Brandt discovered the pure form of phosphorus, which also glowed in the dark. A slow chemical reaction with atmospheric oxygen occurs at the surface of the solid (or liquid) phosphorus, which forms short-lived molecules of HPO and P_2O_2, both of which emit a faint green glow in the visible spectrum (Emsley, 2000) (Fig. 2). Ironically, this same essential reaction is still used today, but with mined phosphate ores, coke for carbon, and electric furnaces.

After much secrecy, Brandt revealed the existence of phosphorus in 1675, and his fellow alchemist Daniel Kraft generated fame and income entertaining European nobility by demonstrating this mysterious new source of light. The name phosphorus is derived from the Greek '*phôs*' meaning "light", and '*phoros*' meaning "bearer", the same name given by ancient Greek and Roman astronomers to the planet Venus, when it appeared in the sky as the morning star (Vallentyne, 1974). By 1676 Johann Kunckel

Fig. 2. "*The Alchymist, In Search of the Philosopher's Stone*". Henning Bandt's chemical discovery of phosphorus in 1669. Painting: Joseph Wright.

was able to make phosphorus, followed in 1680 by Robert Boyle in London (Emsley, 2000). Antoine Lavoisier (founder of modern chemistry) finally recognized phosphorus as an element a century after Brandt's discovery (Emsley, 2000).

The main use of phosphorus in the 17th and 18th centuries, following its chemical isolation by Brandt, was for highly questionable medicinal purposes. However, the discovery in the late 18th century that bones were a more abundant source of mineral phosphorus than urine, led to the mass manufacturing of phosphorus matches, and emergence of the gruesome occupational hazard of 'phossy jaw' (Emsley, 2000). White phosphorus was a dangerous element that could now be produced in relatively high quantities. As an elemental form of phosphorus, white phosphorus is highly reactive and hence not found in nature. It is flammable when exposed to air, can spontaneously combust and is a deadly poison in low doses (Emsley, 2000). Phosphorus became known as the 'Devil's element', due to its life-destroying properties when used in military applications (such as artillery shells, tracers, grenades, smoke cartridges, and fire bombings) and in organophosphate biocides. The most potent of these was the nerve gas VX, which is lethal at 0.1 mg per kg of body weight when applied to exposed skin (Emsley, 2000). By the 20th century it was a common 'element of war' and Emsley notes the tragic irony that 2000 tonnes of "burning phosphorus" was used in 'Operation Gomorrah' to bomb Hamburg and create a horrific firestorm during one summer week in World War II.

Phosphorus is an unusual element. It is not found in nature as a free element due to its high reactivity, yet it has several allotropes, the most common being the white, red and black forms. Allotropes are different elemental arrangements of atoms with vastly different properties; carbon being a well-known example with diamond, graphite and fullerene allotropes. The red and white forms of phosphorus are both insulators, and of nonmetallic character, whereas the black form has a crystal structure made up of corrugated sheets, and behaves like a semi-metal (Mahan, 1969). Phosphorus has two radioactive beta-emitting isotopes, ^{33}P and the higher energy ^{32}P (Winter, 2010). Unlike the other major elements of life (i.e., C, H, O and N), phosphorus does not have a gaseous phase and cannot circulate freely in the atmosphere. As will be discussed later, this has very important implications with respect to phosphorus recovery and reuse.

Biochemically, phosphorus is the basis for all life on our planet. Adult humans contain approximately 0.7 kg of phosphorus, mainly in bones and teeth as calcium phosphate salts. At the molecular level, in the polynucleotide structures DNA and RNA, phosphorus forms the phosphodiester bridges that link one nucleotide to the next. Adenosine triphosphate (ATP) is the primary carrier of chemical energy in cells, via transfer of phosphate groups from energy-yielding to energy-requiring processes. Phospholipids, which contain phosphorus in the form of phosphoric acid, are found in cellular membranes and in the lipoproteins of blood plasma (Lehninger, 1973).

In the biosphere, animals obtain phosphorus from food (plants or lower trophic-level animals); plants, in turn, obtain phosphorus from soils (Johnston, 2000). Mineral sources of soil phosphorus originally come from rock containing phosphorus-rich apatite, that has taken around 10–15 million years to form (White, 2000). These sources started their life as remains of aquatic life (such as shells). They were eventually buried on the sea floor, and transferred to the lithosphere via mineralisation and tectonic uplift over millions of years and eventually weathered down, via wind and rain erosion.

Plants require phosphorus for cell growth, the formation of fruits and seeds and ripening (Johnston, 2000). Hence, plant phosphorus deficiencies can severely hinder crop yields and fruit/seed development. While phosphorus is highly abundant in nature, it is one of the least biologically available nutrients. That is, the forms in which it exists in the biosphere are often 'unavailable' for plants. Plants can only absorb the soluble inorganic form of phosphorus (known as orthophosphates) dissolved in soil solution.

3. Phosphorus cycling in historical food systems

Historically, humans relied on natural levels of soil phosphorus for crop and food production, with additions of organic matter like manure and crop residues. Societies developed regional or local methods of food production that suited the landscape, climate and culture; however, food was always produced and consumed locally.

As long as 40 000 years ago, before agrarian societies developed such practices, hunter-gatherers (such as Aboriginal people in Australia) used 'firestick' farming, which largely ceased after European settlement in Australia in the late 1700's. Through localized and controlled patchwork burning, they manipulated the environment to increase the productivity of edible plants and animals while simultaneously reducing fuel build up that could otherwise lead to dangerously intense wildfires (Cordell, 2001). Australian soils are naturally low in phosphorus, and fire converts unavailable phosphorus bound in soil and plant matter into an inorganic form in ash, temporarily available to plant roots. In addition to increasing the temporary bioavailability of nutrients, patchwork burning also increased availability of edible plants and animals by creating micro-ecosystems of vegetation communities of different ages to increase diversity and possibly local carrying capacity. Further, burning under-story vegetation would expose animals, increasing the ease of hunting. Indirectly, the sudden regeneration initiated by fire would also attract grazing animals such as kangaroos and wallabies which could be hunted (Cordell, 2001). In this way, such burning practices played a vital role in sustaining Aboriginal communities over tens of thousands of years (Flannery, 1994; Flood, 1999).

The use of anthropogenic fire to recycle nutrients accelerated the emergence of agriculture in Europe, as the practice evolved from fire herding of animals to fire-assisted farming. The Neolithic observations that plants blossomed on burned sites, eventually led to the development of the rotational style of European agriculture, based on the use of fire to release calcium, potash and phosphorus, and to control the succession of vegetation on the site. This type of fire-fallow, slash-and-burn style of rotational agriculture has been termed 'swidden' (Pyne, 1997).

In rural Asia (particularly China), the use of human excreta – 'night soil' – in the fields has been common practice for at least 5000 years (Mårald, 1998). Victor Hugo even observed in Les Miserables:

> Science, after having long groped about, now knows that the most fecundating and the most efficacious of fertilizers is human manure. The Chinese, let us confess it to our shame, knew it before us. Not a Chinese peasant goes to town without bringing back with him, at the two extremities of his bamboo pole, two full buckets of what we designate as filth. Thanks to human dung, the earth in China is still as young as in the days of Abraham. Chinese wheat yields a hundred fold of the seed (Hugo, 1862).

Chinese aquaculture, or more appropriately polyculture, has also been based for millennia on the recycling of manure from domesticated animals. Animal droppings either fell directly into or were added to fish ponds, to promote algae and zooplankton growth. This yielded high biomasses of herbivorous and/or planktivorous species of fish. This sustainable approach to protein production independently emerged in the Danube basin and carp culture has been practiced throughout Central and Western Europe since the Middle Ages (Neess, 1949; Hoffman, 1995).

A common practice in the Middle East around 1st century BC–1st century AD during Roman and Byzantine Era's was to keep pigeons not only for meat, but for their manure, a fertilizer rich in phosphorus. Archeological evidence suggests that societies in the Nile region in Egypt and desert regions of southern Israel kept pigeons in columbarium towers (such as that pictured in Fig. 3) (Tepper, 2007). The pigeons were likely free to forage for food among refuse piles and wild desert flora, in addition to being fed some agricultural crop residues and seeds (Ramsay and Tepper, 2010). Tepper (2007) estimates that a columbarium tower, containing 1000 pigeon nesting cells, would have been able to supply approximately 12 tonnes of fertilizer a year, enough to fertilize around 1500 fruit trees and a small garden. Soil fertility of agricultural fields in such desert areas was improved, not only with pigeon manure, but other organic sources of nutrients, such as cow and goat manure, crop and food residues, ash and even furniture (Tepper, 2007). The phosphorus in Nile agriculture originated from annual flooding of the Nile, and ultimately came from erosion in the headlands, hence the role of geologic erosion and periodic flooding must be acknowledged in the renewal of soil fertility (Nixon, 2004).

In Japan, during the Edo era (1603–1868), the residents of early Tokyo supported a population of over 500 000 residents by carefully recycling their human and animal wastes, and small marine fish, back to their agricultural fields (Cederholm et al., 1999; Vaccari, 2011). Edo era, wood block carvings show farmers carrying night soil back to the fields and collecting guano from nearby bat caves. Upland erosion likely provided an additional source of phosphorus in pre-industrial Japan.

In medieval England, it was common practice for nobility to allow peasants to graze sheep on Lord's Land, but they faced severe punishment if caught removing sheep droppings. This

Fig. 3. Remains of ancient dovecotes towers found on Masada, Israel (circa 60–70 AD) used for housing pigeons for meat and fertilizers. This was thought to be essential for survival atop the isolated desert plateau. Photo: Dana Cordell.

demonstrated an uncanny appreciation for the critical role of phosphorus recycling in early agriculture (Driver et al., 1999). The carrying capacity of the British Isles was only five million people in the Middle Ages, whereas the current population is ~55 million, the difference due to the importation of mineral phosphorus for agriculture and food for direct consumption (Emsley, 2000).

Whilst these past communities would not have known about the chemical properties of phosphorus, their ability to maintain soil fertility through organic matter and fire underpinned their very survival.

4. The Sanitation Revolution and consequences for the phosphorus cycle

The development of human settlements, and in particular sanitation arrangements, fundamentally changed the global phosphorus cycle.

In medieval Europe, cities initially began as an attempt to ward off outside threats. At first, the distances between agricultural fields and cities were minor, and the cities 'night soil' could be transported back to the agricultural land to maintain soil productivity. However, the Industrial Revolution (~1760) triggered mass movement of European populations to cities of unprecedented size. The Industrial Revolution started in ~1760 in the UK, with the replacement of animal energy with fossil fuels (initially with coal, then cheap hydrocarbons and hydroelectricity) and the migration of workers to cities, which started a world-wide transition to an industrialized manufacturing economy. As cities grew, they developed their own internal threats: namely crime, fire and disease. By 1854 London was among the world's largest cities – 2.5 million people packed inside a 20 km circumference. This had rarely been done before, and it was uncertain if cities this large were sustainable: a bustling Victorian metropolis saddled with Elizabethan public infrastructure (Johnson, 2006). The living conditions in Victorian London were abysmal: ~700 000 chimneys and ~2000 steam engines – all running on coal, and disease, death and illness were omnipresent. London air was "a compound of fen fog, chimney smoke, smuts and pulverized horse dung" – it killed 3000 people in 1879–80 (McNeill, 2000).

The most noticeable feature of Victorian London was the smell of decomposing organic matter (Johnson, 2006). Communicable disease outbreaks increased with the growing population density. The London plague epidemic in 1665–66 killed 60 000; cholera killed 14 137 in 1849 and 10 738 in 1853. Disease was believed to spread via foul odours – the 'miasma' theory. London's huge sprawl restricted the removal of waste. Night soil men typically worked the graveyard shift in teams of four: a "ropeman", a "holeman" and two "tubmen". The flushing toilet was invented by Sir John Harrington in 1596; however, the 1775 and 1778 patents, by Alexander Cummings and Joseph Bramah for the modern flush toilet, compounded the waste disposal problem by regular flooding of numerous cesspools in London (Johnson, 2006). Most houses just let sewage accumulate in backyard cesspools, or house basements. London's few sewers were only carrying cesspool runoff and surface runoff a short distance to the Thames River. Now, "night soil" was no longer returned to the land as the tonnages and distances were too large; a pervasive fear of bad smells remained, due to foul odours from mass graveyards and sewers.

The turning point occurred on August 28, 1854 when fouled water from the daughter of Thomas and Sarah Lewis was disposed in the cesspool in front of their house. This started the 1854 outbreak of cholera in London – the famous "Broad Street Pump" incident which killed 616 people. Over the next few weeks, Dr. John Snow and Rev. Henry Whitehead conclusively demonstrated the source of infection was the Broad Street well contaminated by wastewater from the adjacent cesspool, culminating with the dramatic step of removing the handle from the pump. This event represented an important milestone in the 'Sanitary Revolution' and the founding event in the new science of public health epidemiology (Johnson, 2006).

Slow sand filtration for water supplies, invented in 1830, rapidly expanded after the Broad Street Pump incident. The massive London sewer system of 120 km of interceptor sewers and 720 km of main sewers was finally built between 1859 and 1865, under the direction of Sir Joseph Bazalgette. The science of bacteriology originated soon afterwards from 1862 to 1870s due to the pioneering efforts of Louis Pasteur and Robert Koch. Emergency chlorination of water supplies had been practiced since about 1850, and continuous chlorination of potable water supplies started in England in 1904 as the principles of public health and sanitation became firmly established in western countries (Sawyer and McCarty, 1978).

The 'Sanitation Revolution' transition from land based to water-based disposal of human wastes fundamentally changed 19th and 20th century civilization, from a phosphorus recycling society to a phosphorus through-put society (Fig. 4). Mineral phosphate, now widely available, was used once, and then discarded in one pass water-based disposal systems. "Night soil" was no longer returned to the land in most European and North American cities, as the tonnages and distances became too large; public health concerns and the expanding Industrial Revolution economies mandated safe disposal, rather than reuse.

5. The Green Revolution and humanity's dependence on phosphate rock

Following the Industrial and Sanitation Revolutions, the next Revolution was to have a profound impact on the phosphorus cycle – the Green Revolution that reformed agriculture and largely abandoned organic fertilizers.

Popular thought in Europe until mid-19th century was that that plants and animals were given life in a mysterious way, from dead and decomposing plants and animals. It was not until 1840 that Justus von Liebig (founder of organic chemistry) confirmed the fertilizing effect of humus on plant growth was due to inorganic salts of phosphorus and nitrogen, and not organic matter (Liebig, 1840). Liebig's 'mineral theory' provided a scientific explanation of how nutrients like phosphorus, nitrogen and potassium were essential elements that circulated continuously between dead and living matter. Despite its radical nature, this theory was widely adopted in Western agriculture and practices were adapted accordingly.

Increasing soil degradation and famines in Europe in the 17–18th centuries triggered a search for external sources of fertilizers to boost crop yields (Mårald, 1998; Emsley, 2000). England, for example, imported large volumes of crushed bones (rich in calcium phosphate) from mainland Europe to apply to British farmlands. The same took place in the US (Fig. 5). This was later taken one step further by dissolving bones in sulfuric acid, to create a liquid fertilizer (Liu, 2005; Rothamsted Research, 2006).

Around the same time, concentrated mineral sources of phosphorus were discovered in guano (bird and bat droppings) off the coast of Peru, and on islands in the South Pacific, such as Nauru and Christmas Island. In 1856, the US Congress passed the 'Guano Islands Act' to facilitate access to uninhabited islands in the Pacific and Atlantic that held significant guano reserves. Phosphate rock deposits rich in phosphate were also identified in the US (Brink, 1977; Smil, 2000). Sir Joseph Henry Gilbert (who had studied under Liebig) and Sir John Bennet Lawes together founded the Rothamsted Research in 1840's in England, to undertake long-term trials of the effectiveness of mineral and organic fertilizers on crop yields

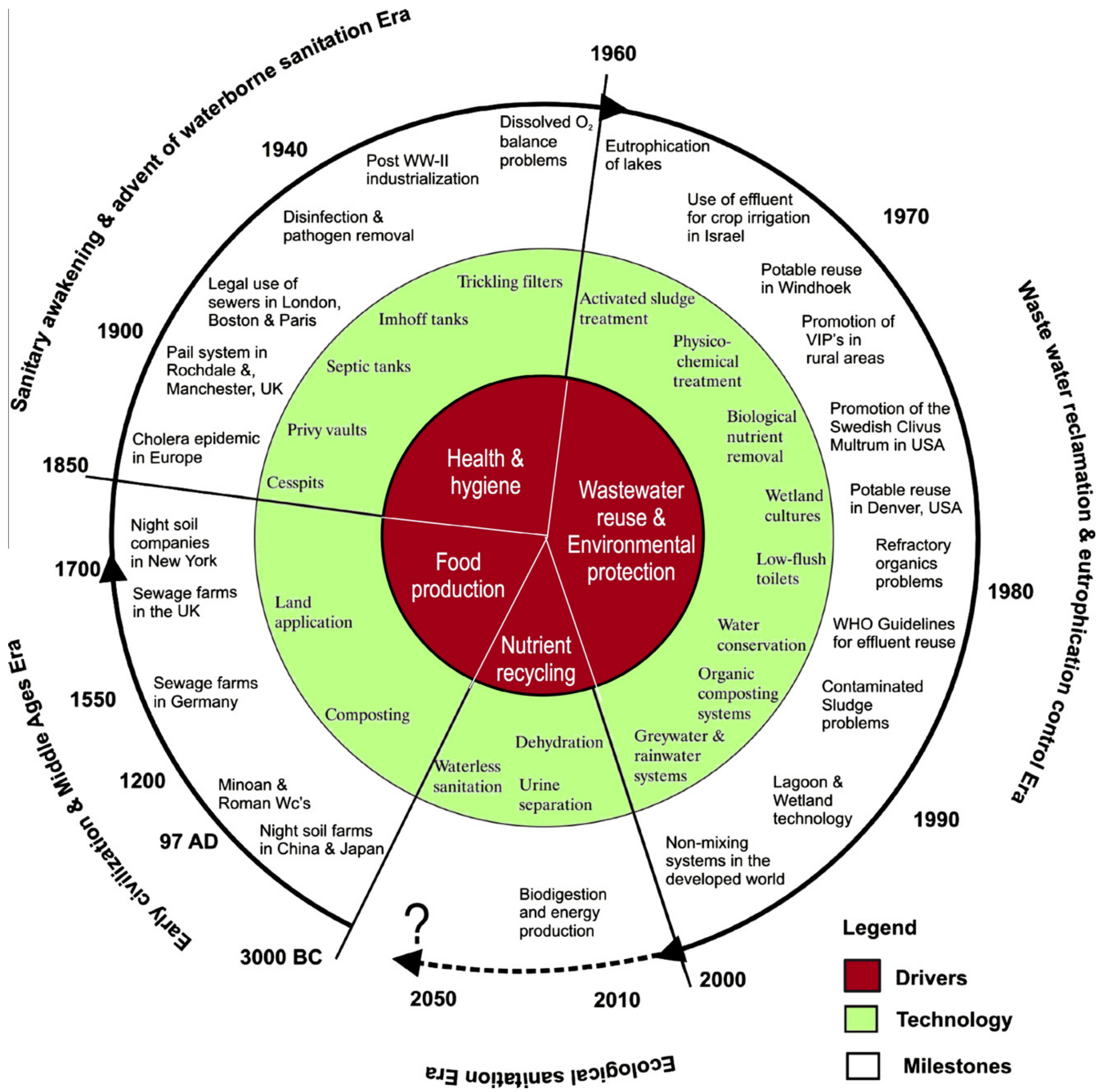

Fig. 4. Evolution of sanitation throughout human history, from 'Early civilization and the middle ages Era', to the 'sanitary awakening and advent of water-borne sanitation era', through to the 'waste water reclamation and eutrophication control Era', and possible future 'Ecological sanitation Era'. *Source*: Redrawn from Gumbo (2005).

(Rothamsted Research, 2006). Eventually, it was demonstrated that more phosphorus needed to be applied to fields than the amount removed in harvest crops.

However, it was not until the post-World Water II period that use of mineral phosphorus sources grew exponentially (Fig. 6). Phosphate rock was seen as a cheap and plentiful source of phosphorus and it became widely used in favour of organic sources (Brink, 1977; Smil, 2000). To keep up with rapid population growth, increasing food shortages and urbanization in the mid-20th century, high-yielding crop varieties were developed, known as the Green Revolution. This was supported by the invention of the Haber–Bosch process, which allowed the production of high volumes of artificial nitrogenous fertilizers, with external inputs of irrigation water, nutrients, pesticides, herbicides and hydrocarbon energy, rather than manual labour (Brink, 1977; Fresco, 2009). Phosphate rock was now mined to keep up with nitrogen fertilizer demand. Fertilizer use sextupled between 1950 and 2000 (IFA, 2006). The Green Revolution contributed to the doubling of crop yields and increasing per capita nutritional intake (IFPRI, 2002).

While phosphate rock seemed like limitless source of highly concentrated phosphorus, it was relying on a non-homogenous, non-renewable resource. Today, societies are effectively dependent on phosphorus from mined phosphate rock. Without continual inputs, we could not produce food at current global yields (Cordell, 2010).

There is little doubt today of the importance of additions of mineral phosphorus fertilizers in producing food at current global yields. Indeed, phosphate rock, together with nitrogen and potassium fertilizers, and relatively inexpensive hydrocarbon fuels, were responsible for feeding billions of people over the past century. The need to raise soil fertility in nutrient deficient areas like

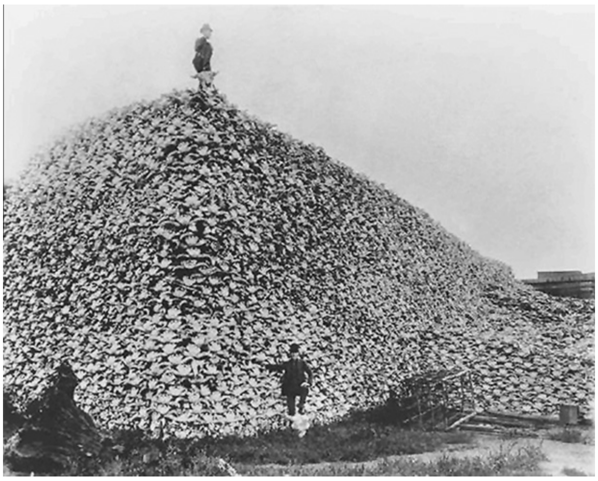

Fig. 5. Large pile of bison skulls that will be ground into fertilizer in the US around 1870. Photograph courtesy of Burton Historical Collection, Detroit Public Library.

Sub-Saharan Africa is relatively well understood by the food security community. However, few discussions have explicitly addressed the emerging challenge of where and how phosphorus will be obtained in the future, to ensure continuous food availability for a growing world population.

6. The nutrient cycle is broken

The Green Revolution and Sanitation Revolution both had profound consequences on the global phosphorus cycle. While industrialized agriculture established a dependence on mined phosphate rock in favour of organic sources, water-based disposal of human wastes fundamentally changed modern civilization from a phosphorus recycling society to a phosphorus through-put society. Today, phosphorus is mined in only a few geographical locations, processed into fertilizers and transported around the globe to apply to the world's agricultural fields. Unlike the natural biochemical cycle, which recycles phosphorus back to the soil via dead plant matter, industrial agriculture harvests crops prior to their decay phase and transports them all over the world for food production and consumption. This means continual applications of phosphorus-rich fertilizer are required to replace the phosphorus that is removed from the soil when crops are harvested. Once consumed, most phosphorus molecules in food exit our bodies in urine (70%) and faeces (30%) – approximately half a kilogram per person each year (Jönsson et al., 2004). As early as 1928, Aldus Huxley wrote in "Point Counter Point":

> "With your intensive agriculture…you're simply draining the soil of phosphorus. More than half of 1% a year. Going clean out of circulation. And then the way you throw away hundreds of thousands of tons of phosphorus pentoxide in your sewage! Pouring it into the sea. And you call that progress. Your modern sewage systems!" His tone was witheringly scornful. "You ought to be putting it back where it came from. On the land." Lord Edward shook an admonitory finger and frowned. "On the land, I tell you." (p. 57)

A once closed-looped sustainable cycle had been opened and phosphorus molecules now move in a linear fashion, from mines to oceans at rates many orders of magnitudes greater than the natural biogeochemical cycle, which takes tens of millions of years.

7. From the Industrial Revolution to widespread phosphorus pollution

With the Industrial Revolution gaining momentum, public health concerns mandated disposal of excreta, rather than reuse. Phosphorus was now discharged to oceans, lakes and rivers instead of land, and thus, permanently lost from the human food system. Cultural eutrophication of freshwaters mirrored the expansion and development of modern industrial societies through Europe and North America: the Wisconsin lakes – Mendota and Monona in 1882, Lake of Zurich, Switzerland in 1896, Lake Erie in 1930 and Lake Washington in the 1950s, to name a few (Vallentyne, 1974). The most famous water-borne pollution incident being

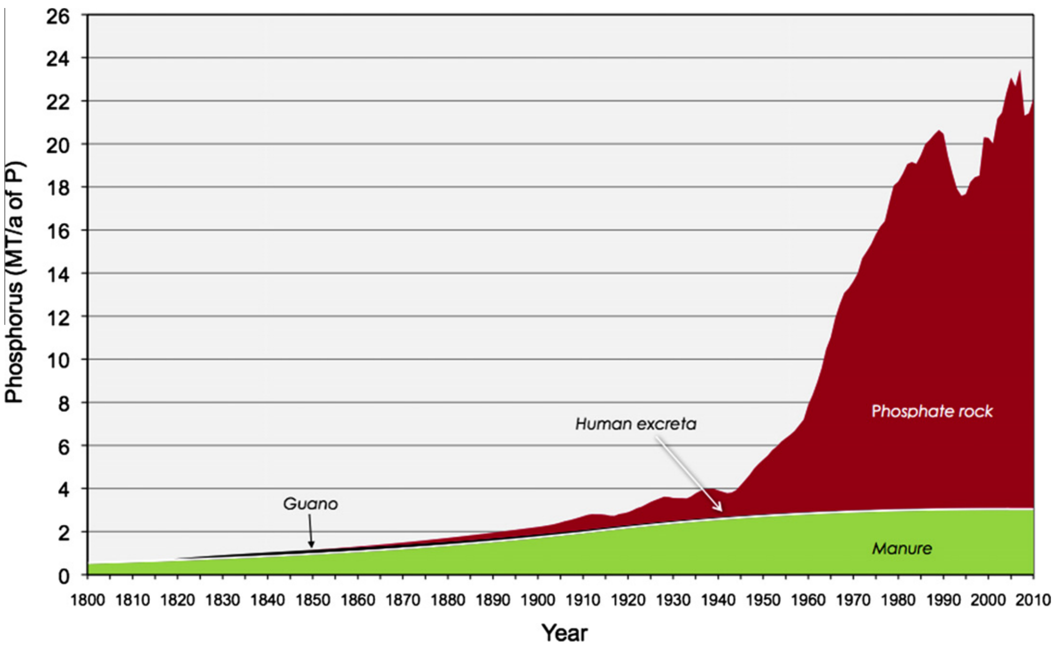

Fig. 6. Historical sources of phosphorus fertilizers used in agriculture globally (1800–2010). The dramatic increase in phosphate rock production in the middle of the 20th century is indicated. *Source*: updated from Cordell et al (2009).

"The Great Stink" when British Parliament was disrupted in the summer of 1858 due to the stench from the raw sewage enriched Thames River (Fig. 7); this, no doubt, guaranteed political support for construction of London's new sewer system (Johnson, 2006).

The sanitary engineering community responded to the increasing prevalence of water closets and emerging public health requirements by building sewer projects (Neset et al., 2010), and eventually developing wastewater treatment processes to stabilize and treat human waste (Metcalf and Eddy, 1991). Elegant Victorian schemes to pay for new sewer systems, by marketing cash crops from 'sewage farms', were largely dismissed; not because the idea was faulty, but because the early examples were flawed due to location, wet weather, and poor management (Goddard, 1996). In early 20th century Sweden, waste products from the emerging 'consumer society' (i.e., broken glass and metal tins) contaminated household excreta, and contributed to the abandoning of returning nutrients to farmlands (Neset et al., 2010).

The resulting problems of receiving water pollution soon intensified; sanitary engineers initially addressed the problem by building longer sewers (Edmondson, 1991), and eventually developed more sophisticated wastewater treatment processes: this included secondary treatment, to further reduce biochemical oxygen demand. The rapidly expanding economies and populations in the post WW II western world, plus the introduction of detergent phosphates, led to increasingly widespread eutrophication and subsequent scientific investigations to resolve the ''Great Phosphorus Debate' (Vallentyne, 1974). Although numerous independent investigations identified phosphorus as the key element in eutrophication (National Academy of Sciences, 1969), a single photograph of an experimentally divided lake in northwestern Ontario,

Fig. 7. Carricature of Prof. Faraday giving his business card to the odiferous Father Thames. *Source*: A cartoon in Punch Magazine, July 1855, by artist John Leech.

Lake 226, led to bans on the use of detergent phosphates, as well as implementation of tertiary wastewater treatment to remove nutrients from point source effluent streams (Schindler and Vallentyne, 2008; Schindler, 2009). Tertiary treatment was initially achieved by chemical precipitation, which permanently removed phosphorus from the human food system and created significant waste sludge disposal problems. Later, phosphorus was removed by the more elegant and sustainable Biological Nutrient Removal process (Barnard, 1975), and the problem with phosphorus management appeared to be solved – or was it?

Unfortunately, waste treatment for animal manures remained at medieval levels of sophistication, as it does to this day. This archaic situation, coupled with increasing use of fertilizers from the 'Green Revolution', global trends in agri-business herd densification, biofuel farming and increasing dietary consumption of meat, has created a global epidemic of point and non-point source eutrophication, with degraded water quality conditions reminiscent of Victorian London. From the Baltic, to Canada's Lake Winnipeg, to New Zealand's Rotorua lakes, Chesapeake Bay, the Gulf of Mexico and much of China, the global footprint of eutrophication is rapidly expanding and permanently removing phosphorus from the world's food system. In 1974, J.R. Vallentyne predicted that by the year 2000 we would be living in an environmental disaster he called the Algal Bowl: it was an accurate prediction, indeed (Vallentyne, 1974).

8. A new era: global phosphorus scarcity

While phosphorus has largely been managed as a pollutant to date, the 21st century is witness to a new dominant understanding of phosphorus as a globally scarce resource. Some scientists and philosophers have warned about future phosphate scarcity for decades – if not centuries. As early as 1798, Thomas Malthus expressed concerns that global population would eventually be constrained by food supply (Linnér, 2003). Later echoed by Meadows et al (1972) in their seminal work 'Limits to Growth', which suggested that certain elements were of finite supply on planet earth, and that one day they could be depleted. They warned that the current trajectory of resource use could not continue indefinitely and would eventually lead to collapse. With specific reference to finite phosphate rock resources and implications for humanity, Aldous Huxley's character Lord Howard in his 1928 novel Point Counterpoint proclaims:

> "you think you can make good the loss with phosphate rocks. But what'll you do when the deposits are exhausted?....What then? Only two hundred years and they'll be finished. You think we're being progressive because we're living on our capital. Phosphates, coal, petroleum, nitre - squander them all. That's your policy." (Huxley, 1928)

Sixty years ago M. King Hubbert (1949) showed the world that that oil production would eventually reach a peak of instantaneous production and then decline, constrained by energy and economics of extracting lower quality and less accessible reservoirs (Deffeyes, 2003). The critical point in time will therefore be much sooner than when 100% of the resource is depleted. Hubbert proved this empirically using production data from the US oil reservoirs. Like oil, phosphate rock is a non-renewable resource and a critical resource on which society currently depends. Production of phosphate rock is estimated to peak around 2030–2040 concurrent with a rising demand from a growing and hungry world population, trends towards more meat and dairy-based diets, the need to boost soil fertility in some regions and demand for biofuels and other non-food commodities (Cordell et al., 2009). The more pessimistic analysis by Dery and Anderson (2007) suggested peak phosphorus already occurred in 1989. However this was likely to be a mini-peak due to the collapse of the Soviet Union and reduced demand from Europe and North America (see Cordell et al., 2009 for further explanation). The latest International Center for Soil Fertility and Agriculture Development (IFDC) report suggests there are 60 000 Mt of phosphate rock reserves, compared to previous US Geological Survey (USGS) estimates of 16 000 Mt (Van Kauwenbergh, 2010). However, these new IFDC figures only increase the estimates for Moroccan phosphate reserves based on a 30 year old report, are only estimates based on "inferred" reserves, which have not been verified by on-site prospecting and ore grade analysis, nor been independently verified, hence must be viewed with considerable caution. Further, the new reserve estimates do not remove the threat of peak phosphorus; they only delay the peak by several decades.

Whist there is a vigorous debate today around the lifetime of phosphate rock reserves or the timeline of peak phosphorus, what is clear is that the remaining rock is lower in phosphorus concentration (%P_2O_5), higher in contaminants, and more difficult to access, in environmentally or culturally sensitive areas; it will require more energy to extract and produce, and will cost more to refine and ship (Cordell et al., 2009). Further, unlike oil, phosphorus cannot be substituted for, when it becomes scarce or expensive. As put eloquently by Asimov:

> We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation - but for phosphorus there is neither substitute nor replacement (Asimov, 1974).

An ultimate goal of sustainable phosphorus use is ensuring that all the world's farmers have sufficient access to phosphorus to grow enough food to feed the global population, whilst minimizing adverse environmental and social impacts (Cordell, 2010). However, already today, many poor farmers (particularly in sub-Saharan Africa) have phosphorus-deficient soils and cannot access fertilizer markets due to poor purchasing power. This has led not only to low crop yields, but also increasing losses due to soil erosion, poor farmer incomes and increased hunger. Indeed, many of the world's 1.02 billion undernourished people are smallholder farmers (IAASTD, 2008; FAO, 2009).

Further complicating the picture, is that just five countries control 85% of the world's remaining reserves – Morocco, China, US, Jordan and South Africa (Jasinski, 2010). If the 2010 IFDC report were accurate, this would mean Morocco alone controls 85% of the world's phosphate rock reserves. A spike in the price of food, oil, fertilizers and other raw materials in 2008 triggered food and farmer riots. An unprecedented 800% price spike in phosphate rock affected the world's farmers and led to China imposing a 135% export tariff on phosphates; this effectively halted exports from one of the largest producing countries (Fertilizer Week, 2008). Morocco controls the world's largest remaining high quality phosphate reserves – including the portion that occurs in Western Sahara, contrary to UN resolutions. The US, formally the world's largest producer, consumer, importer and exporter of phosphate rock, now has only decades left of it is own reserves (Cordell, 2010; Jasinski, 2010). Whilst phosphate prices eventually dropped from 800% to only 200–300% higher than 2007 levels (partly due to the economic crisis), this short-term crisis can be seen as a warning of things to come. The 2010 United Nations Food Price Index now exceeds the 2008 spike and is widely believed to be contributing to the unprecedented political tumult in the Middle East.

While modern society has been preoccupied with concerns about international terrorism and climate change (which are enormous social and environmental problems intimately linked to combustion of fossil fuels) the companion 'show stopper' of peak phosphorus has attracted little attention, until recently. The convergence of peak phosphorus, peak oil and water shortages in a climatically stressed mid-21st century world is already raising concerns among the world's military strategists (Dyer, 2008).

9. Learning from the past: towards a sustainable phosphorus future?

Averting a major phosphorus crisis is possible; however, it will require considerable political will and substantial changes to our current physical infrastructure and institutional arrangements. While we do not need to revert back to the ways of the 'dark ages' and carry our own excrements in buckets to the field, we do fundamentally need to return to a nutrient reuse society, in order to sustain our population into the future and protect the aquatic environment. Sustaining global and local phosphorus cycles can only be achieved through recycling close to 100% of the phosphorus temporarily lost from the food production and consumption system – including human excreta, manure, food and organic waste. Drangert et al. (2010) reflects that, while humanity was previously in an era of nutrient recycling for tens of thousands of years, we may merely be in a brief period in history where the phosphorus cycle has been broken and the sanitation-food link temporarily disconnected.

Investing in renewable phosphorus sources (through local phosphorus recovery from wastes) can simultaneously reduce dependence on a finite resource, reduce water pollution and increase communities' phosphorus security, which is particularly important for regions highly dependent on imports – from Europe to sub-Saharan Africa. Today's extremely long and globalized food commodity chains have led to numerous points of phosphorus losses and inefficiencies; so much so that only a fifth of the phosphorus mined to produce food actually reaches the food we eat (Cordell et al., 2009). The remainder is lost (permanently or temporarily) during mining and fertilizer production, application and harvest, livestock rearing, food processing and retail and finally during consumption and excretion. This presents numerous opportunities for increasing efficiency of phosphorus use and reducing unnecessary spillages, wastage and ecosystem degradation.

There is no single solution to replace the massive consumption of phosphate rock. Sustainable measures aimed at recovering and reusing phosphorus in the food system can range from low-tech, small-scale solutions like direct urine reuse, through to large scale, high-tech solutions such as struvite recovery from wastewater treatment plants (Britton et al., 2009; Cordell et al., 2011). Solutions will need to be region-specific, to ensure they are appropriate for the local environmental, political, economic, demographic and cultural conditions; they must also be harmonious with the region's sanitation and food security situation.

It is particularly important that developing countries re-examine their aspirations for 'western-style' sewage treatment solutions, and not automatically adopt the 'water carriage central end-of-pipe treatment' paradigm, which is among the most expensive and energy intensive components of modern public infrastructure (Abeysuriya et al., 2006). This 'once through' paradigm was designed to solve the emerging disease and pollution problems of Victorian London and other 19th century Industrial Revolution cities; however, it is not necessarily the optimal solution for the 21st century developing world, or in the developed world as aging infrastructure systems become due for replacement. Alternatives such as decentralized systems, waste-stream separation at source, and 'improved' centralized systems should be considered (Abeysuriya et al., 2006); the focus should be on recovering water, heat energy, carbon, nitrogen and especially phosphorus, to once again 'close the circle' and become truly sustainable.

Given the importance of phosphorus to our very existence, it is perhaps surprising that there are no explicit governance structures, such as policies or organizations, that specifically address the long-term availability and accessibility of phosphorus for global food security (Cordell, 2010). Thus, there is a strong need for effective governance to ensure a coordinated response to phosphorus accessibility for all farmers and looming phosphorus shortages, exacerbated by a global population of 6.7 billion humans, ~63 billion livestock, and now competing demands for phosphorus for non-food purposes (such as growing biofuel crops which require ongoing fertilization or lithium-ion-phosphate electric vehicle batteries that each contain 60 kg of phosphate) (Cordell, 2010). We will need to confront our diets, and reverse the recent global trend towards more phosphorus-demanding meat-based diets; we should consider shorter food production and consumption chains, such as urban agriculture fertilized with urban phosphorus-containing 'waste' streams, in order to secure a sustainable phosphorus cycle and feed humanity in the future. The stark reality is that the ecological footprint of ~63 billion livestock, even at a conservative 10:1 animal to human ratio, represents a global planetary footprint of over 630 billion humans, which is not sustainable. In addition, the phosphorus leakage from supporting this massive agricultural biomass is the dominant contributor to the global epidemic of non-point source eutrophication, which is degrading the world's fresh waters and near-shore coastal zones at an accelerating rate (World Resources Institute, 2008). Clearly, a 'Fourth Revolution' is required to resolve this dilemma, as the 'phosphorus footprint' of the world's standing livestock dwarfs their human counterpart.

10. Conclusions

This paper has shown how the Industrial, Sanitation and Green Revolutions have altered human use of phosphorus, shifting from close-looped phosphorus-food systems to unsustainable linear paths that have simultaneously lead to a global environmental challenges of phosphorus pollution and scarcity. Increasing environmental, economic, geopolitical and social concerns about the short- and long-term use of phosphate rock in agriculture means there is an urgent need to reassess the way crops obtain their phosphorus and humanity is fed.

Anadromous fish such as sockeye salmon (*Oncorhynchus nerka*) are an interesting example of a source of phosphorus flux from the ocean back to the terrestrial ecosystem (Stockner and Ashley, 2003). When salmon migrate upstream to spawn and die they return nutrients from the ocean, which is recycled in the aquatic environment and a portion typically consumed by carnivores such as bears and numerous scavengers, which is then deposited in riparian and upland areas, thus enriching the terrestrial environment. Hopefully, we are intelligent and observant enough to learn from nature and follow their lead towards an environmentally sustainable future where phosphorus, and other limiting nutrients, are captured and recycled ad infinitum.

A globally emerging paradigm is now in place (Abeysuriya et al., 2006). As evidenced by nutrient recovery conferences held recently (e.g., Ashley et al., 2009), increased technical publications and theme articles in internationally published literature, both public and political awareness of the 'phosphorus issue' is becoming more widespread. Phosphorus recovery and reuse from domestic wastewater is already expanding and targeted agricultural wastes, such as dairy and hog manure, is on the horizon. With phosphorus now becoming a 'strategic' commodity in the global marketplace, the pathway ahead is very clear. The fate of humankind on this planet may, indeed, rest on this recognition factor.

Clearly, a Fourth Revolution is required, which we will term "The Sustainable Agri-Food Revolution". It is widely acknowledged that the most valuable needs of the 21st century planet, with potentially 9 billion humans and 90 billion livestock (if the 1:10 ratio remains), will be clean water and adequate nutrition. Neither of these basic needs will be achievable, especially in the developing countries, if we do not start now to reform the use of phosphorus in the global agricultural-food production system. No doubt some governments and industries will mock and oppose these ideas, just as some have used obfuscation and denial to avoid the realities of climate change (Hoggan, 2009). Universities and NGO's will play a key role in this regard, as sources of factual information and unbiased policy recommendations. History has repeatedly shown that conflicts often arise between countries over resource inequities (Klare, 2001; Dyer, 2008), and we need not follow that path when peaceful, and truly sustainable alternatives, are possible.

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