Roland W. Scholz · Amit H. Roy
Fridolin S. Brand · Deborah T. Hellums
Andrea E. Ulrich *Editors*

Sustainable Phosphorus Management

A Global Transdisciplinary Roadmap

Springer

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Preface

This book is a key product of the first 2 years of the Global TraPs project. The chapters incorporate prevailing views on *critical questions* and *issues* related to current phosphorus management practices. These views have been elaborated among more than 200 key stakeholders of the phosphorus supply–demand chain. For each node, *Exploration*, *Mining*, *Processing*, *Use*, and *Dissipation and Recycling* as well as the cross-cutting issue: *Trade and Finance,* the reader will find *state-of-the-art knowledge*, *transdisciplinary processes* (i.e., forms of science-practice collaboration) and *topical case studies.* This may help to develop robust orientations on how food security may be achieved and how the current low use efficiency may be increased by improved utilization strategies and the development of new technologies. A closure of the anthropogenic phosphorus cycle may help to avoid eutrophication, hypoxia, and other negative impacts on ecosystems and promotes resources conservation. Finally, the book takes a global perspective on phosphorous and reveals the different use patterns of different types of farmers and countries.

The Global TraPs project and the writing of this book was a consultative process and included participation of representatives from industry and trade, scientists from various disciplines and numerous universities, public agencies and international organizations, Non Governmental Organizations (NGOs), farmers and user associations. This consultative process included four workshops during 2010 and 2012 and the first Global TraPs World-conference in Beijing, China, June 18–20, 2013. We, as the leaders of the project, are very impressed with how well this process worked. The members of the Global TraPs project unselfishly shared their knowledge and time to develop a comprehensive understanding of phosphorus use. Most remarkable was the willingness to listen to each other. Thus, authentic process of mutual learning and knowledge integration took place. We want to thank all authors and reviewers, and the participants of this—presumably first—large-scale transdisciplinary process. This book is an important milestone of this process.

The chapters present a widely shared blueprint of on current phosphorus use and how it may be improved for developing orientations for sustainable phosphorus management. Yet as it is typical for transdisciplinary multistakeholder discourse, the discussion of different chapters revealed the complexity and multilayeredness of the supply–demand chain and identified different and incoherent data, perspectives and valuations that asked for integration. This complexity challenged a re-examinations, re-assessment, and rethinking of key conclusions. A final round of review of all chapters was initiated at the 2013 Beijing conference. For supplementing the current view on sustainable phosphorus management, spotlights were written for explaining key concepts or for introducing nonconventional views. The introductory chapter now includes both a comprehensive and coherent blueprint of an actor- or agent-based phosphorus flows view and outlines the transdisciplinary process, i.e., the specific science-practice collaboration which is needed to foster its sustainable use.

The book thus goes far beyond the mere description of physical phosphorus flows and their impact. As expressed by the subtitle “Global Transdisciplinary Roadmap,” the chapters provide a schedule of how critical questions may be answered, in particular by transdisciplinary case studies. The vision is to accomplish mutual learning and consensus building among the key stakeholders of the phosphorus supply–demand chain. This may be valuable not only for the members of the Global TraPs project or those who are interested in sustainable phosphorus management, but also for scientists and key stakeholders who are interested in sustainable resources management.

Amit H. Roy
Roland W. Scholz

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Nomenclature

mg	Milligramme (10^{-3} g)
kg	Kilogramme (10^{3} g)
kt	Thousand tonnes (10^{9} g)
Mt	Megatons = Million tonnes (10^{12} g)
Gt	Gigatons = Billion tonnes (10^{15} g)
K	Potassium
N	Nitrogen
P	Phosphorus
PR	Phosphate Rock
DAP	Diammonium Phosphate
NP	Nitro Phosphate
MAP	Monoammonium Phosphate
SSP	Single Superphosphate
TSP	Triple Super Phosphate
MFA	Material Flow Analysis
SFA	Substance Flow Analysis

Basic *conversion factors* among phosphate rock, phosphorus-pentoxide, and phosphorus as used in common annual statistics:

1 t PR contains according to common notation about 300 kg (i.e., 30 %) P_2O_5
1 t P_2O_5 contains a mass of 436 kg (i.e., 43.6 %) P
1 t PR includes 130 kg (i.e., 13 %) P

Basic *data* on phosphorus production and reserved in 2011 (in parenthesis [] in 2012) according to the reports of USGS (2012, [2013[1]]):

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[1] All references from this page are referring to http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/. Please note that USGS (2012) reports that 191 Mt PR have been produced in 2011. This has been re-adjusted to 198 Mt PR in USGS 2013 report. Both data are used in the different section of this book. Please check the year of reference which is taken for USGS publication.

PR production in 2011: 191 Mt [198 Mt]
P_2O_5 production in 2011: 57.3 Mt [59.4]
P consumption from phosphate rock ore in 2011: 25.0 Mt [2011 = 25.9 Mt]
PR production in 2012[2]: 210 Mt [2011 = 191 Mt]
P reserves amount to 71 Gt P [67 Gt P][3]

The cumulatively world production of P from 1900 till 2012 according to USGS (2013) amounts to 7.6 Gt P.

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[2] USGS (2013).

[3] The lower number is due to the fact that the reserves for Iraq, (which have been first recorded in 2012) was adjusted to a lower number because they were based on a Russian classification of reserves than the common US classification applied for other countries (Jasinski, personal communication, 5. Feb. 2012).

Chapter 1
Sustainable Phosphorus Management: A Transdisciplinary Challenge

Roland W. Scholz, Amit H. Roy and Deborah T. Hellums

Abstract This chapter begins with a brief review of the history of phosphorus, followed by a description of the role of phosphorus in food security and technology development. It is then followed by discussions on critical issues related to sustainable phosphorus management, such as phosphorus-related pollution, the innovation potential of phosphate fertilizers and fertilizer production, uneven geographical distribution of phosphate resources, transparency of reserves, economic scarcity, and price volatility of phosphate products. In order to identify the deficiencies in the world's phosphorus flows, we utilize the "not too little–not too much" principle (including the Ecological Paracelsus Principle), which is essential to understanding the issues of pollution, supply security, losses, sinks and efficiency of phosphorus use, and the challenges to closing the phosphorus cycle by recycling and other means. When linking the supply–demand (SD) chain view on phosphorus with a Substance or Material Flux Analysis, the key actors in the

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global phosphorus cycle become evident. It is apparent that sustainable phosphorus management is a very complex issue that requires a global transdisciplinary process to arrive at a consensus solution. This holds true both from an epistemological (i.e., knowledge) perspective as well as from a sustainable management perspective. To gain a complete picture of the current phosphorus cycle, one requires knowledge from a broad spectrum of sciences, ranging from geology, mining, and chemical engineering; soil and plant sciences; and all facets of agricultural and environmental sciences to economics, policy, and behavioral and decision science. As phosphorus flows are bound to specific historical, sociocultural, and geographical issues as well as financial and political interests, the understanding of the complex contextual constraints requires knowledge of related sciences. The need for transdisciplinary processes is equally evident from a sustainable transitioning perspective. In order to identify options, drivers, and barriers to improving phosphorus flows, one requires processes in; capacity building that may be changed and consensus building on the phosphorus use practices that must be changed and maintained, along with recognition of how changes in phosphorus use in the current market may be framed. The latter is illustrated by means of the Global TraPs (Global Transdisciplinary Processes for Sustainable Phosphorus Management) project, a multi-stakeholder initiative including key stakeholders on both sides of the phosphorus SD chain which includes mutual learning between science and society.

Keywords Sustainable phosphorus management • Supply–demand chain analysis • Food security • Environmental impacts

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1 New Perspective on Phosphorus Management

1.1 What's New About This Book?

Many books, theses, and papers have been written from various perspectives on phosphorus. The present book targets *global sustainable phosphorus management*. *Transdisciplinarity*, whose core is *the integration of knowledge between practice and science*, is seen as a means by which a sustainable transition toward global efficiency may be achieved. This is a new concept, and the subject of a comprehensive project, the Global TraPs (Global Transdisciplinary Processes for Sustainable Phosphorus management) project, which was officially launched on 6 February 2011.

This book explains what *sustainable phosphorus management* may mean, why we need transdisciplinarity (as defined in the context of the Global TraPs project) and why phosphorus (P) is so distinctive that it may serve as a learning case for any *global biogeochemical cycle management*. In the case of P, sustainable biogeochemical cycle management includes *pollution prevention, resource conservation, technology development,* and *knowledge generation* in a way that future generations may have efficient access to P. Closing the fertilizer loop from the mining of phosphate rock to its use, at least to some extent, is definitely one means. However, this may only be accomplished if we have a clear view of how losses and sinks of phosphorus are related to the actions of the key stakeholders. Clearly, phosphorus atoms do not disappear from earth. We denote those fractions that have been excluded from the value chain by human action (such as phosphorus in mining waste, sewage, and manure) as losses. This is why we take a supply–demand chain perspective. Here, demand is explicitly mentioned because phosphorus is essential, and human life is inextricably linked to the use of considerable amounts of P, particularly for food production. Chapters 2–6 of this book, like the Global TraPs project itself, are structured to follow the stages of the supply–demand chain, which are *Exploration*, *Mining*, *Processing*, *Use* and *Dissipation and Recycling*. A large share of phosphorus flows is tied to economic transaction. Thus, a chapter *on Trade and Finance*, which addresses critical aspects such as the origins of price peaks, is included in this book.

The conceptual vision is elaborated in the *Closed-Loop Supply–Demand* Chain Management of the *anthropogenic* portion of (CloSD Chain Management) phosphorus flows in this chapter. The concept makes reference to ideas in industrial ecology such as "loop closing" (Lifset and Graedel 2002), or "from cradle to cradle" (McDonough et al. 2003, SI 7), stressing the need for recycling. Special emphasis is given to the economic perspective. This is also indicated by including a demand perspective. As Scholz and Wellmer (2013) point out, phosphorus is a demand-driven market rather than a supply-driven market. There is a steady but—as phosphorus is essential and mineral fertilizers a key element of current food supply security, see Spotlight 1—limitedly adaptable demand function and, compared with other minerals and metals, rather abundant resources. Thus, we face a demand-driven market and must understand how the demand side may be affected by technology, population growth, lifestyles, etc.

Though CloSD Chain Management may be considered a necessary condition of sustainable phosphorus management, it is by no means a sufficient one. Sustainability goes beyond the environmental, economic or technological dimensions and includes *social* (Brundtland 1987) and *equity* (Laws et al. 2004) dimensions. The *social dimension* is certainly the most difficult and challenging, but is of major importance. We can easily illustrate this dimension by reviewing the case of sub-Saharan Africa's smallholder farmers. Most of these smallholders live in countries whose soils have the highest need for fertilizers. *Smallholder farms* in this region constitute 80 % of African agrarian land (IFAD 2011), yet they are the most disadvantaged with respect to soil fertility and other factors (i.e., erosion). As a result, the percentage of undernourished within the African rural population is about 16 % (FAO 2010b). In addition to having a large share of highly weathered soils with low nutrient content, some soils in sub-Saharan Africa tend to bind phosphorus (significantly reducing phosphorus available to plants). Gaining access to P, therefore, is fundamental to improving the productivity and livelihoods of smallholder farmers. As documented in 2009, Africa's soils received on the average (including countries with large-scale agroindustrial plantations) only 2.48 kg P ha^{-1} year^{-1}, whereas the soils of Europe and North America, which have higher loads of soil phosphorus from centuries of fertilizer use received 18.7 and 19.12 kg P ha^{-1} year^{-1}, respectively, during the same period (FAO 2012b). Thus, African farmers, and many others who do not practice balanced fertilization, are removing a larger portion of one or more nutrients from the soil (through harvested crops) than is being added (through organic amendments and mineral fertilizers) on an annual basis. Clearly, many smallholder farmers in developing countries are neither able to access manufactured fertilizers, nor do they have access to technologies that promote efficient fertilizer use. In many developing countries, providing access to phosphorus and other nutrients is essential to improving food security.

This book, in support of the Global TraPs project mission, states that we must not only learn from the different stakeholders about their knowledge and cultural backgrounds, but we also must learn from history to better understand the role of phosphorus in biotic and abiotic processes. Ultimately, we must use this knowledge to change current use practices. To that end, we ask the reader to review the brief history of phosphorus that follows.

1.2 Learning from Phosphorus History: Light, Fertilizers, and a Conflict of Interest

In ancient times, the planet Venus was referred to as "phosphorus" by the Greeks (Wisniak 2005). As indicated by its etymological meaning (phosphorus: light bearer; from phos "light" [related to phainein, "to show, to bring to light": see phantasm] + phoros "bearer," (OED 2012)]), the earliest interest in phosphorus was as a lighting element. History indicates that in 1669, the alchemist Henning Brand (c.1630–c.1710) "rediscovered" the element and the procedure to generate phosphorus (Krafft 1969), which entailed boiling silver pieces in urine, drying the silver, mixing it with sand (silica), heating the mixture and collecting the resulting yellowish mass in a condenser. This mass caught fire easily when exposed to air (at ambient temperature). He was believed to have discovered a "black" substance, a "Prima material," or "elemental 'fire,'" i.e., "one of the four Aristotelan 'elements,' earth, water, air, and fire" (Krafft 1969). Giants of the history of science such as Gottfried Wilhelm Leibniz (1646–1716)—who wrote the "Historia inventionis phoshori" (1710)—and Christiaan Huygens (1629–1695) were involved in documenting the procedure, which was run with "a full ton of urine" (Leibniz 1710). Through the work of Lavoisier (1743–1794, Lavoisier 1776), phosphorus became the 13th element in the history of the discovery of elements (Emsley 2000a).

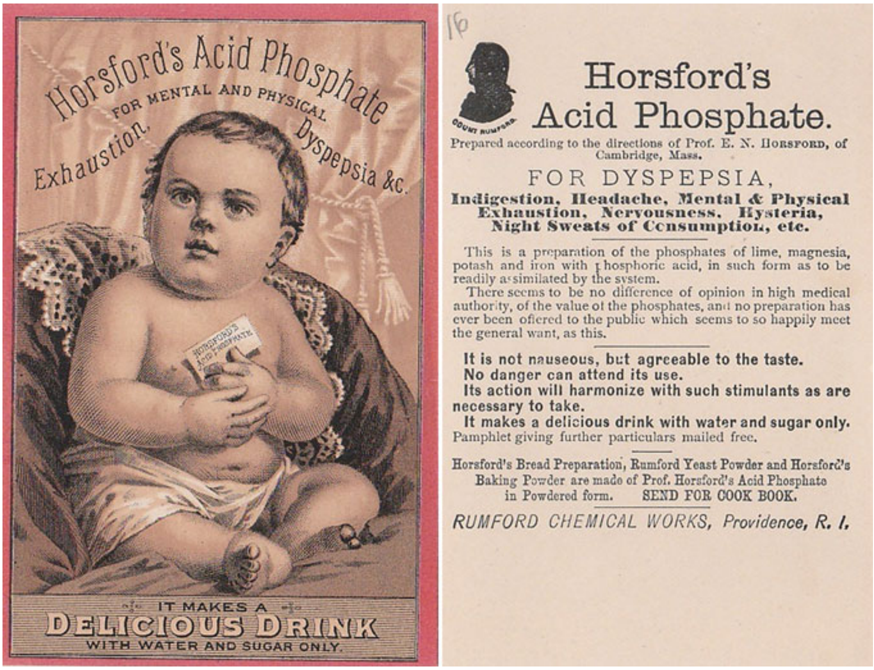
Phosphorus was of *commercial interest* from the very beginning. Alchemists rigorously explored the element, and pharmaceutical companies found uses for it soon after its discovery (Richmond et al. 2003). Eben Norton Horsford (1818–1893), chemist working on phosphorus and a scholar of Justus von Liebig and Professor at Harvard of the Application of Science to the Useful Arts, was the inventor of baking powder. He became cofounder of Rumsford Chemical Works and promoted the selling of phosphate acid for medical purposes (Jackson 1892, see Fig. 1). Large-scale match production began in the early nineteenth century (see Fig. 2) and phosphorus bombs became warfare agents.

After Brand's discovery, "for a century, urine was the only source from which phosphorus was attained" (Färber 1921). But in 1769, Carl Wilhelm Scheele (1742–1786) and Johan Gottlieb Gahn (1745–1818) discovered phosphoric acid in animal bone and many other animal parts (Färber 1921; Petroianu 2010). Théodore de Sassure stated in 1804 that, "we had no means to believe that plants can exist without phosphorus" (Färber 1921, p. 11). These statements were later proven by the emerging experimental "Animal and Vegetable Chemistry" (Dumas and Boussingault 1844), which provided insight into the metabolic nature of plant physiology (Liebig 1840) and set the foundation of *nutrient balance*, which suspected that deficiency of phosphorus was the limiting factor in plant growth (Liebig's Law of the Minimum; see Paris 1992).

But farmers knew about phosphorus long before the modern scientific community. Phosphorus has been used in agriculture, even if unknowingly, since prehistoric times. In fact, archeologists use phosphorus as a tracer element for human settlements (Schlezinger and Howes 2000), and fertilizer use can be traced back to at least the third millennium B.C. (Wilkinson 1982). The Inca civilization used guano as fertilizer (de la Vega 1609/1990). Roman agriculture included manures for crops in the first century (Lelle and Gold 1994), and the use of bones as fertilizer was reported by Walter Blithe (1605–1654, Brand 1937).

Without understanding its scientific properties, farmers utilized the phosphorus and other macronutrients in manure, excrements, and bones as fertilizer. Eventually, scientists learned from these ancient practices, and farmers adapted quickly. As an example, desperate farmers were said to have raided Napoleonic battlefields such as Waterloo (1805) and Austerlitz (1815) to collect human bodies for their phosphorus contents [Hillel, 1991; cited in Foster (1999)]. In his book, *Farmers of forty centuries: organic farming in China, Korea and Japan,* Franklin H. King provides us with another example: "Manure of all kinds, human and animal, is religiously saved and applied to the fields in a manner which secures an efficiency far above our own practices" (King 1911/2004). "This was not done directly, but potential fertilizer such as river mud" was often dried and pulverized before being carried back and used on the fields as makeshift fertilizers (p. 8).

In 1804, Alexander von Humboldt (1769–1859) observed that Peruvian fields were fertilized with guano. He took samples to Europe where chemists noticed high levels of nitrogen (N) and phosphorus (von Pier 2006). In the period between 1857 and 1867, about 50,000 metric tons (mt) of guano were imported annually by Europe (Färber 1921). But technological progress opened other options.



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Acid Phosphate.

Prepared according to the directions of Prof. E. N. Horsford, of Cambridge, Mass.

FOR DYSPEPSIA,

Indigestion, Headache, Mental & Physical Exhaustion, Nervousness, Hysteria, Night Sweats of Consumption, etc.

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It is not nauseous, but agreeable to the taste.

No danger can attend its use.

Its action will harmonize with such stimulants as are necessary to take.

It makes a delicious drink with water and sugar only.

Pamphlet giving further particulars mailed free.

Horsford's Bread Preparation, Rumford Yeast Powder and Horsford's Baking Powder are made of Prof. Horsford's Acid Phosphate in Powdered form. SEND FOR COOK BOOK.

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Fig. 1 Phosphate acid was seen as remedies for many diseases (*Source* Hulman & Co)

Fig. 2 Phosphorus may have positive and, in certain forms, negative effects. This picture shows a former employee of the Reliable Match Company of Ashland, Ohio, who died in 1912 due to exposure to *white P*. The disease, which was labeled “phossy jaw,” recently reappeared with patients who were treated with *bisphosphonate*, a P-based medicine (Body 2006). Thus, the new term, “bis-phossy jaw,” emerged (Hellstein and Marek 2004). Picture taken from the “A last victim,” *The Survey* 28, no. 2, 1921 after a reproduction of Moss (1994)

The history of phosphorus fertilizer (organophosphate) invention, and essentially the beginning of the fertilizer industry, was written primarily by three icons of their times, Sir James Murray (1788–1871), Sir John Bennet Lawes (1814–1900), and Baron Justus von Liebig (1803–1873). When referring to experiments in converting "bones to biophosphate of lime as fertilizer, using sulfuric acid," Lawes is noted to have carried out the first field experiments mixing wastes, compost, and manure in 1817. He then experimented with different mixtures of nutrients (Alford and Parkes 1953; Childs 2000). In 1842, trials were carried out to compare the new fertilizer with manure (Childs 2000). Here, superphosphate, a composition of calcium hydrogen phosphate and calcium sulfate was applied. Practically, rock phosphate was treated with sulfuric acid. Lawes bought patents from Murray and Liebig and, in 1843, founded the Rothamsted Experimental Station in an area of the United Kingdom that was extremely deficient in nutrients due to centuries of nutrient-extractive agriculture. In France, Boussignault demonstrated the synergetic effects of P, N, and other minerals. Quickly, the chemical and manure industries developed to fill the growing agricultural need (Daly 1984) to avert famine.

The development of scientific knowledge in the nineteenth century may be considered a history of errors, as even the greatest knowledge of that time was incomplete. This point may be highlighted with the earliest of Liebig's seminal contributions. Initially, Liebig's patented fertilizer proved to be a failure, as it contained no N or potassium (K), and phosphorus was present in an unavailable form. Liebig corrected the latter idea—that soluble forms of phosphorus would be washed away from the soil by rainwater—when he realized that soluble phosphorus was essential for plant growth (Emsley 2000b; Oertli 2008).

Seventy-five years ago, the executive secretary of The US National Fertilizer Association wrote:

> Not so many years ago, the fertilizer industry was largely a waste-products industry. The bone, blood, and tankage of the packaging industry, the fleshings and scraps of the leather industry, the slops of the beet sugar industry and the meal residues of the vegetable oil industry made up the greater part of mixed fertilizer." And he noted that buyers had been "more impressed … by … odor than by chemical composition or guarantee of plant food content. (Brand 1937)

The idea to solubilize phosphorus in bones by sulfuric acid (transforming slow release calcium phosphate to superphosphate) was also transferred to phosphate rock. Single superphosphate, triple superphosphate (monocalcium phosphate), and diammonium phosphate became the pillars of the phosphate industry.

But historically, fertilization has been only one of the uses for P. Boyle discovered in 1680 that when sulfur and phosphorus were rubbed together, they caught fire. It took about 140 years until "Lucifers," the original name for contemporary "strike anywhere" matches (Battista 1947), were invented. Excessive exposure to *White* (also called yellow) phosphorus (P_4O_{10})-containing matches that were produced in some countries caused many diseases such a "phossy jaw," a variant of bone cancer. This particular disease was first diagnosed in Vienna

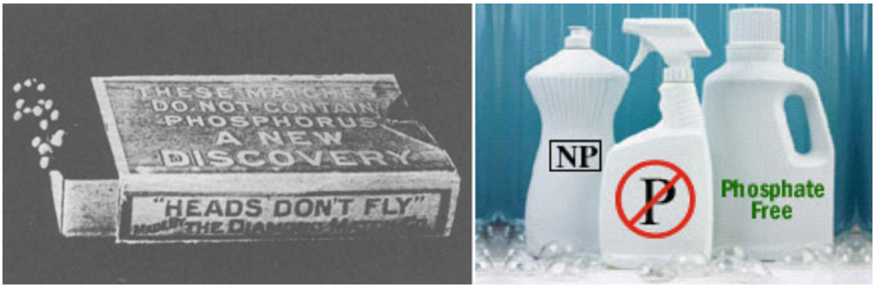

Fig. 3 The Berne Convention of 1906 banned the highly toxic *white phosphorus* from matches. Whereas no biomass may emerge without P, matches without *white phosphorus* and household detergents without phosphorus could be produced to avoid critical collateral impacts (*left* picture taken from Andrews (1910) after a reproduction by Moss (1994), *right* picture after courtesy of the South East Regional Centre for Urban Landcare, Brisbane, Australia)

(Moss 1994), where its P-related etiology was proven (Marx 2008). Young girls who carried matchboxes on their heads became bald (Datta 2005). The import and sale of matches containing white phosphorus were banned by many European countries under the Berne Convention of 1906. "In the United States, nearly all interested parties supported legal abolition, but… no state wanted to be the first to act (for the fear of driving industry from its borders), and the federal government lacked the power to regulate intrastate economic activity …" (Moss 1994). The necessity that global phosphorus management should advocate for international action may be well-learned from this case.

White phosphorus (P_4) is still in use for match production in developing countries and is permitted for contemporary epidemiological studies (González-Andradea et al. 2002). The lethal dose is about 1.0 mg/kg weight in adults (Gossel and Bricker 1994). The critical toxicity of *White* phosphorus can be demonstrated in a new form of "phossy jaw," the "bis-phossy jaw," which is observed in people who are treated with bisphosphonate to combat bone necrosis (about 10 % of the human bone is P, see Fig. 3).

It should be noted that *phosphorus* does not appear in a pure form in nature, but rather, is generally observed in the oxidized form of *phosphate* (PO_4) which becomes *organophosphate* such as DNA if it is bound with organic compounds. This book deals with the chemical element phosphorus, which is denoted as P, though occasionally phosphorus also denotes phosphate in the context of this publication.

2 The Role of Phosphorus in Food Security and Technology Development

"Producing enough food for the world's population in 2050 will be easy." This is the first sentence of a recent Editorial in *Nature* (2010) in a series on world food