The phosphate balance

Current developments and future outlook

February 2011

InnovationNetwork
Reinventing Agribusiness and Rural Areas

Courage

kiemkracht

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This study is conducted within the theme 'Sustainable Enterprise', concept 'Phosphate source'.

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The ministry of Economic Affairs, Agriculture and Innovation initiated and finances InnovationNetwork.

ISBN: 978 – 90 – 5059 – 414 – 1

Report Number 10.2.232E, Utrecht, the Netherlands, February 2011.

Preface

All living organisms depend on phosphorus. Indeed, phosphorus is part of every living cell. No other element could emulate or stand in for phosphorus in countless physiological and biochemical cell processes. Crop production therefore relies on a plenteous P supply. The phosphorus content of fodder and foodstuffs likewise has to be sufficient. However, local eutrophication caused by too much of the element in the environment can disrupt ecosystems. This phenomenon occurs in the Netherlands, where large quantities of phosphorus are imported with raw materials for cattle feed and artificial fertiliser. Much of this accumulates in the soil, from where it leaches and drains into surface water and groundwater. While accumulated phosphorus in the soil contributes poorly to crop food supplies, when it leaches and drains away it is wasted. Depletion must then be added to the environmental damage caused. Depletion is a serious matter, because the phosphate supply is finite. There is a growing awareness worldwide of the need to deal far more efficiently with phosphorus.

This need was the immediate background to this study, which aimed to identify and quantify global phosphorus supplies and demand, now and in the future. The authors have backgrounds in geochemistry and mineralogy. They estimate that current, proven phosphorus supplies will be exhausted somewhere between 2040 and 2070, with as yet unidentified but presumed phosphorus reserves running out between 2100 and 2150. Much of the considerable bandwidth in the time horizon is explained by uncertainties surrounding the future demand for phosphorus to support food production for the growing global population, and biomass for energy and other applications. If phosphorus prices rise above current levels, exploitable supplies will increase correspondingly. For instance, a doubling of phosphorus prices translates into sufficient supplies for several centuries.

Even without signs of an absolute phosphorus shortage in the short and medium term, we would be well advised to start now to piece together the phosphorus cycles so as to reduce environmental burden, ease supply management, and anticipate impending phosphate price rises. Currently only a small proportion of phosphorus is reused. The report below presents several phosphorus recycling options.

This report is a joint product of InnovationNetwork, Courage and Kiemkracht. We hope the report helps increase awareness of the phosphorus issue and will boost efforts towards firm solutions.

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Summary

Phosphate is essential for agricultural production and therefore plays a key role in the global production of food and biofuels. There are no agricultural alternatives for phosphate, and a substantial fraction of our annual phosphate consumption is dispersed into the environment where it is largely lost to agriculture. Phosphate is an irreplaceable, and to a considerable extent non-renewable, resource that is being exploited at an ever increasing rate.

The ongoing depletion of phosphate resources combined with recently increased phosphate prices urge us to reconsider our phosphate consumption patterns. In addition to economic and geo-political reasons, further reducing phosphate consumption would moreover be beneficial to the quality of our environment.

There are basically two lines to attack the phosphate depletion problem:

- increase the reserve base;
- recycle a larger proportion of the phosphate passing though society and the environment.

Even if we increase the reserve base, for which there are plenty of opportunities, it is clear that the phosphate industry will sooner or later have to make a switch from a reserve-based industry to a recycling industry.

Chapter 2: Global phosphate production, reserves and resource development

Phosphate is mainly derived from rocks enriched with phosphate (20 – 35% P_2O_5). Major producers of phosphate rock are Morocco (including Western Sahara), China, and the US which account for

65% of world production. Europe does not currently produce any raw phosphate ores, and imports all raw phosphate and phosphate fertilisers from abroad.

The measured and indicated economic phosphate reserves are estimated at some 15000 Mt of phosphate rock, whereas the reserve base, which also includes the marginally and sub-economic phosphate deposits, is estimated at some 47000 Mt of phosphate rock. This represents 5000 Mt and 16000 Mt of P_2O_5 respectively.

Mining production of phosphate rock increased slightly in the last decade and the current annual production amounts to some 167 Mt. As a result of increasing phosphate prices, resource development has been stimulated and new phosphate occurrences are currently being evaluated in e.g. Mali and Namibia. As a result of increasing phosphate prices, the size of the reserve and reserve base will increase in the future. At prices of 50 - 100 US$/ton, it is estimated that our current reserve base would roughly double to 100 000 Mt of phosphate rock.

Chapter 3: Global use and consumption of phosphate
Phosphate rock is mainly used for the production of mineral fertilisers such as diammonium-phosphate (DAP) and triple superphosphate (TSP), which on average accounts for 74% of the global inorganic phosphate consumption. This average global figure excludes the role of organic phosphate in the form of animal feed and food. It should be noted that for some countries such as the Netherlands, the organic phosphate consumption plays a more important role than inorganic fertiliser consumption.

The four largest (net) consumers of phosphate fertilisers include China, the US, India and Brazil i.e. big countries with a substantial agricultural sector. The global per capita consumption pattern reveals considerable differences between the western world (> 20 kg P_2O_5/capita; e.g. US, Australia, Canada and New Zealand) and the developing countries i.e. much of Africa (< 1 kg P_2O_5/capita). Europe plays an intermediate role in inorganic phosphate fertiliser consumption.

The consumption of phosphate rock has, on average, increased by some 3.4% in the last 100 years, yet phosphate prices have remained somewhat stable (constant 1998 prices fluctuating between 26 and 43 US$/t). Only during the last two years have phosphate prices started to rise rapidly from ~30 US$/ton in 2005 to 113 US$/ton in 2008. Even more, exceptionally high spot prices of 500 US$/t cif were reported by the US Geological Survey in 2008. Although these high spot prices are bound to go down in the near future, cheap phosphate prices will be a thing of the past.

Chapter 4: Future trends of phosphate consumption and sufficiency of resources
Using various scenarios for global phosphate consumption as well as the additional effect of increasing biofuel production, the sufficiency of the current phosphate reserves (indicated and measured economic

reserves) and reserve base (including the marginally and sub-economic reserves) is estimated. Although particularly the role of biofuel production is difficult to assess here, it seems likely that the current reserves will be exhausted somewhere between 2040 and 2070, and the reserve base somewhere between 2100 and 2150.

These estimates are in line with previous projections, but the size of the reserve and reserve base are based on rock phosphate prices of 20 – 40 US$/t. At prices of 50 - 100 US$/t the future reserve base would roughly double and phosphate sufficiency will last well into the next few centuries.

Chapter 5: Phosphate in the Netherlands
Net phosphate consumption in the Netherlands currently amounts to some 183 000 t P_2O_5 (~ 11 kg P_2O_5/capita), most of which is in organic matter (animal feed - 59%). The role of inorganic phosphate such as fertilisers and feed additives is less important (35%). This shows that the consumption of inorganic phosphate through mineral fertilisers does not necessarily represent total phosphate consumption, particularly for countries that are dependent to a substantial degree on the import of animal feed for their livestock such as the Netherlands, Belgium and Denmark.

Since the early nineteen-eighties, the total consumption of phosphate in the Netherlands has decreased by around 47%. This decrease was caused by lower consumption levels of animal feed (addition of phytase) and decreasing consumption of inorganic phosphate fertilisers as well as other forms of phosphate (e.g. detergents). Recent new Dutch legislation regarding nutrient application on agricultural land, in which maximum allowed levels of nutrients are gradually decreased towards 2015, expects a further decrease in agricultural phosphate consumption.

Due to historical over-application of mineral fertilisers and manure, a substantial amount of phosphate has accumulated in agricultural soils in the Netherlands; on average the concentrations of P_2O_5 have tripled and a substantial fraction of the soils is phosphate saturated. It is estimated that the current accumulated phosphate fraction in the agricultural topsoils amounts to some 1.9 Mt of P_2O_5, which is ~40 years of current fertiliser application. Part of this fraction will gradually become available for plants, and offers opportunities for reducing phosphate application without significant loss of crop yield.

Chapter 6: Phosphate recycling and recommendations for sustainable use
The increasing consumption and subsequent future scarcity of phosphate resources, are ample reasons for the transition to a more sustainable use of phosphate:

- Geological/Geo-political: the Netherlands is fully dependent on the import of phosphate from abroad, and worldwide resources of phosphate are limited.\
- Economic: future phosphate prices are likely to remain high at 50 – 100 US$/ton, increasing fertiliser costs and subsequently animal feed prices.

- Economic/Environmental: elevated phosphate prices have increased the economic feasibility of different forms of phosphate recycling.
- Environmental: The need to balance inputs and outputs (soil balance) to reduce nutrient losses to surface water and groundwater in order to meet EU water quality targets.

Various options for reducing losses and further recycling have been reviewed in the previous sections. The effective options for the short term are:

1. The most significant reduction in phosphate consumption and subsequent reduction of losses can and will be achieved in the Dutch agricultural sector, which is responsible for the bulk of the net Dutch phosphate consumption and around 40% of the total phosphate losses. Reducing the agricultural consumption of phosphate is already enforced through the Fertilisers Act 2006. This has a major effect. Compared to 2005 the newly implemented phosphate use standards will lead to a reduction in phosphate use from manures and fertilisers of 30-40% (i.e. 71-95 Gg P_2O_5 per annum).
2. Reduction of phosphate contents of animal feed and improving its availability (e.g. using biorefinery), the production of fertiliser from manure and an increased export of manure will lead to a reduction in P-input of 20 – 30 Gg P_2O_5 per annum.
3. Phosphate loss can be diminished by using an alternative approach of phosphate removal from urban and industrial waste water, e.g. by using aluminium salts. Phosphate precipitated in the sewage sludge can then be used as raw phosphate ore for the production of fertiliser. In that way 18 Gg P_2O_5 per annum can be recycled.
4. In-row placement of phosphate fertilisers. It is estimated that this can reduce P input by 10 Gg P_2O_5 per annum.

The different measures to reduce inputs and losses result in total annual savings of 119 to 153 Gg P_2O_5. This shows that by a combination of different measures the P-balance of the Netherlands can be substantially improved to meet future challenges of geo-political, economical and environmental nature.

I. Introduction

Phosphorus occurs naturally in the form of different phosphate minerals, hence phosphorus is commonly expressed – and referred to – as phosphate (see Text Box 1). Phosphorus plays a key role in the major photosynthetic and metabolic pathways and is an essential nutrient for all the earth's living organisms. The rapidly increasing human population in the world and the concomitant increase in prosperity in some parts of the world have greatly increased the demand for crop- and animal-derived food during the last few decades (Ma et al, 2010). Modern agriculture relies heavily on phosphate addition to animal feed and the application of phosphate fertilisers for crop production, which makes phosphorus an essential constituent of the global food market. Moreover, the production of biomass for biofuels also relies on phosphate application, and thereby also tends to increase the global demand for phosphate.

Phosphate should be regarded as an indispensable resource for plants, animals and people. Although the current geological phosphate resources are still sufficient to meet the growing demand of the near future, phosphate resources are – as with oil resources - finite. Because large phosphate reserves are found in only a few countries - including Morocco, China, South Africa and the USA phosphate should also be regarded as a strategic, geo-political commodity.

After a long period of relative stability, phosphate prices have become unstable:
Prices increased from 2007 onwards, peaked in 2008 followed by a decline to the price level of 2007 and are currently (June 2010) again increasing (USGS, 2009). The reason for this sharp price increase is not immediately clear, but growing demand for fertiliser for production of crop- and animal-derived food, biofuels as well as a

sudden rise in oil prices in the summer of 2008 may have resulted in a panic-driven phosphate market. Although the high spot prices of 2008 are bound to go down in the near future, cheap phosphate will be a thing of the past (e.g. Cordell et al., 2009).

Global phosphate consumption in the form of animal manures and fertilisers, biosolids and detergents has also led to widespread eutrophication of soils, lakes, rivers and estuaries (e.g. EEA, 2005; FAO, 2006; EEA, 2009). Consequently, much of the nutrient-poor ecosystems in the western world have been degraded or have even disappeared. The use of phosphate fertilisers has also led to soil and groundwater being contaminated with harmful trace metals such as cadmium (see e.g. Nziguheba and Smolders, 2008).

For economic as well as environmental reasons, it seems necessary to reconsider our phosphate consumption pattern, and to come to a more sustainable use of our phosphate resources. In this study, conducted on behalf of the Dutch Innovation Network, current developments in global phosphate production and consumption patterns are reviewed (Chapters 2 and 3), and various scenarios for the future availability of phosphate resources are presented (Chapter 4). Furthermore, the phosphate consumption patterns in the Netherlands are reviewed and discussed (Chapter 5), and different options for a more sustainable use of phosphate in the Netherlands are described (Chapter 6).

TEXT BOX 1 – Terminology

Name	Abbre-viation	Conversion Factors	Phosphorus, which has an atomic weight of 30.97, is one of the essential nutrients for living organisms. Elemental phosphorus does not occur in nature, and P is present in different inorganic (phosphate) and organic forms. Phosphorus present in different commodities is therefore often referred to as phosphate (expressed as the amount of P_2O_5).
Elemental phosphorus	P	$P = 0.4364 P_2O_5$ $P = 0.1997 BPL$	Phosphate refers to a salt of phosphoric acid (H_3PO_4), such as calcium phosphate. More generally, the term phosphate is used for any oxidic form of phosphorus.
Phosphate	-	See P_2O_5	Rock phosphate is a natural rock containing one or more calcium phosphate minerals. It can be used immediately after grinding or after chemical processing in the manufacture of commercial phosphate fertilisers (FAO, 2009). Rock phosphate is mostly used to quantify mine production, reserves and reserve bases of phosphate (chapter 2)
Rock phosphate	RP	RP = 0.25 - 0.4 P_2O_5	Rock phosphate is a natural rock containing one or more calcium phosphate minerals. It can be used immediately after grinding or after chemical processing in the manufacture of commercial phosphate fertilisers (FAO, 2009). Rock phosphate is mostly used to quantify mine production, reserves and reserve bases of phosphate (chapter 2)
(Phosphate) Phosphorus pentoxide or phosphoric oxide	P_2O_5	$P_2O_5 = 2.2914P$ $P_2O_5 = 0.4576BPL$	The amount of phosphate present in different forms is often expressed as phosphoric oxide. As such, P_2O_5 is the common denominator when comparing different phosphorus-containing fertilisers, for instance in terms of total production, consumption and trade (Smil, 2000).
Bone phosphate of lime	BPL	$BPL = 2.1852 P_2O_5$	Bone phosphate of lime is the trade name for tricalcium phosphate [$Ca_3(PO_4)_2$] which is the primary criterion used to differentiate phosphate rocks (IFDC et al., 1998). The name is reminiscent of the time when bones were the principal source of phosphate in the fertiliser industry. At present BPL is not commonly used to classify the quality of phosphate rock and is not used in this report.

2. Global phosphate production, reserves and resource development

2.1 Global phosphate production

Virtually all phosphate consumed today is derived from geological formations with a high phosphorus concentration. To qualify as a phosphate ore, these formations must contain a minimum concentration of phosphorus that makes its mining economically feasible. Historically, this concentration ranges from 25 to 35 wt% of P_2O_5, but the actual exploitation of the ore depends on factors such as ease of mining, extractability of the phosphate component and location of the ore deposit. The commercial product of these phosphate mines is called phosphate rock.

2.1.1 Classification and composition of phosphate ore

According to their genetic origin, phosphate deposits can be classified in the following three types: sedimentary, magmatic and guano-type deposits. Sedimentary and magmatic deposits are widely distributed throughout the world, guano-type deposits occur mainly in the Pacific region.

Sedimentary phosphates
Sedimentary phosphate deposits are formed as part of marine sedimentary sequences, mainly from the Eocene and Cretaceous ages, by precipitation of the phosphate minerals from cold phosphorus-

enriched water flowing across warm, shallow shelf environments or mixing with warm ocean currents. The precipitation of inorganic phosphate minerals is accompanied by the deposition of the skeletal remains of the aquatic life that thrived in the phosphate-rich areas and of inorganic debris from the continent, including quartz and clay particles. In addition, calcite may precipitate from the rising currents. A special category among the sedimentary type of deposits is formed by phosphates originating from the weathering of phosphatic sedimentary limestone. The genetic origin of these deposits is much the same as that of the 'normal' sedimentary phosphates.

The most important sedimentary phosphate deposits are located in the US, China and in a belt south and east of the Mediterranean (Morocco to Jordan). In general, sedimentary phosphate ore is friable, sometimes even unconsolidated, as for example the Tertiary age ore located in south-east US. Crushing and milling, if necessary, are therefore relatively easy and cheap.

Igneous phosphates

Igneous phosphates find their origin in magmatic activity. They occur as apatite-enriched masses, sheets or veins in so-called alkaline intrusive complexes. Alkaline complexes are relatively small, round intrusive bodies of a specific silica-poor composition. Major phosphate containing alkaline complexes are to be found in Russia, South Africa and Brazil.

Some magmatic phosphates are associated with magnetite iron ore and in other cases with rare earth elements, as in the unexploited carbonatite of Cargill, Ontario, Canada. The phosphate enriched iron ores of Kiruna, Sweden are a special category, although they are not directly the result of magmatic activity but were probably formed by the extrusion of hot iron and phosphorus-rich fluids on the seabed. When associated with magnetite, igneous phosphate may become a by-product of iron mining.

Igneous phosphate rock is much harder than its sedimentary counterparts and, as a result, may be more expensive to exploit in terms of mining and processing. However, the resulting product will be of higher quality, as the apatite minerals are purer and easier to separate.

Guano

All large guano deposits were formed by the accumulation of sea bird droppings. The present composition of guano deposits, for the most part calcium phosphate, may vary considerably, mainly as a result of leaching by surface water.

The major guano deposits occur in Oceania. However, guano reserves are dwindling and do not play a significant role in the phosphate market. Consequently, this type of ore will not be given further consideration.

Composition of phosphate ores

The main phosphate minerals in phosphate rock are francolite, fluorapatite, dahllite and hydroxyapatite. As the chemical composition of these minerals may vary, they are better represented by a compositional series having as end members fluorapatite ($Ca_{10}[PO_4]6F_2$) and francolite ($Ca_{10-a-b}Na_aMgb[PO_4]6-x[CO_3]_xF_{0.4x}F_2$ where a, b and x denote moles of Na, Mg and CO_3^{2-} respectively). In particular in sedimentary phosphate rock, a large variety of minerals make up the so-called gangue (= non ore minerals). Generally speaking, the presence of these minerals means that the ore is not commercially viable. The most important are Ca-Fe-Al-phosphates, quartz, carbonates and evaporites such as halite (rock salt) and gypsum.

A large number of ions may substitute for Ca, P, F and O in the crystal lattice, thus causing impurities mostly unwanted not only for technical, but also for environmental reasons. For example, iron, magnesium and carbonate are considered disadvantageous in the wet processing of the ore, whereas cadmium, uranium and fluorine may cause environmental problems (see Chapter 4). Nevertheless, some of these elements, when occurring in sufficient concentration, may be recovered from the ore as a useful by-product.

2.1.2
Beneficiation and processing of phosphate ore

The term phosphate rock generally refers to the marketable, mostly beneficiated, product from the mining and concentration of phosphate ore. In general, phosphate rock contains 30 to 40 wt% P_2O_5 (e.g. Schipper et al., 2001). In some cases, the grade and/or composition of phosphate ore is such that it can be put to use without further treatment, e.g. as a fertiliser. In most cases, some form of beneficiation or processing is necessary to render the material useful. Beneficiation refers to some type of simple mechanical purification and concentration to increase the phosphate content of the ore.

In a first processing step, much of the phosphate rock is nowadays processed using sulphuric acid to produce phosphoric acid. The largest portion of this phosphoric acid is used for the acidulation of phosphate rock in the manufacture of fertilisers.

An alternative way of producing phosphoric acid is by thermal treatment. In the thermal treatment of phosphate rock to produce elemental phosphorus, the ore is pelletized with clay and sintered in a first process step at a maximum temperature of 1000 °C. In a second step, the sinter is mixed with flux, usually gravel, and cokes and molten in electric furnaces in a reducing environment. The phosphorus is liberated from the melt in gaseous form in accordance with the following generalised reaction:

$$Ca_{10}(PO_4)_6F_2 + 8SiO_2 + 15C \rightarrow 6CaSiO_3 + 15CO + 1½P_4 + Ca_4Si_2O_7F_2$$

Elemental phosphorus, which is recovered from the gas mixture by condensation, may then be burned to diphosphoruspentoxide for the production of phosphoric acid. The carbon monoxide is further burned to carbon dioxide. The remaining reaction products end up in the slag, which flows continuously into slag beds or may be tapped batchwise into slag pans. The slag contains calcium from the ore and silica from the gravel and forms a by-product of slightly positive value used mainly in road construction.

The production of phosphoric acid thermal treatment is no longer in use as it requires too much energy. However, this production method has gained renewed interest for recycling of P for sewage sludge and manure.

2.2 Global phosphate reserves

Reserve and resource definition
As mentioned above, any naturally occurring material containing one or more phosphate minerals and possessing chemical and physical characteristics that make it acceptable for commercial use as a source of phosphate, may be considered as a phosphate ore in the broadest sense. The reserves of any ore are subdivided into various categories depending on the degree of exploration carried out on the geological formation containing the ore in question.

Proven or measured reserves are defined by a prescribed drilling pattern and are considered mineable under the economic conditions at the time of definition. Proven reserves form the basis for the considerable investment necessary for the development of the ore body into a mine, and strict rules, which are imposed by stock exchanges and financial institutions, apply to their definition. Indicated and inferred reserves, also referred to as probable and possible, are less well defined but may be expected to be mineable within a certain margin of error. All these reserves involve ore bodies that have been discovered and, in many cases, are actually being mined. More detailed exploration will upgrade at least a portion of the indicated and inferred ore to the category of proven reserves.

Where the previous categories all refer to discovered ore deposits, considerable potential for exploitable ore may exist in geological environments similar to those containing the already known ore bodies. One example is the oil and gas fields assumed to exist beneath the North Pole ice. Interpretation of the geology in this area indicates a high degree of probability of the existence of oil and gas fields, yet no specific deposits have actually been discovered. Similarly, such hypothetical and speculative resources of phosphate can be defined. In fact, much exploration leading to the discovery of new reserves is based on hypotheses and sometimes on speculation.

From an economic point of view, reserves are subdivided into the categories economic, marginally economic and sub-economic. Marginally economic reserves are expected to be exploitable at marginal profit and sub-economic reserves may be exploitable in the near future at a given price development. The total number of measured and indicated reserves in the economic and marginal category is called the reserve base. Depending on expectations regarding future price developments, some of the sub-economic reserves are included in the reserve base. Table 2.1 presents a schematic overview of the various categories of reserves and resources.

	Discovered resources			Undiscovered resources
	Measured	Indicated	Inferred	
Economic	Reserves			Hypothetical and speculative
Marginally Economic	Marginal Reserves			
Sub-economic				
Other	Un-economic and non-conventional resources			

Table 2.1:
Scheme of reserve and resource definition in the mining industry. The shaded area represents the reserve base.

All categories together are called the resource of an ore or mineable substance. Obviously this resource is a highly flexible quantity that is – like the reserve base – defined mostly by the economic situation of the moment. For example, phosphate from non-conventional resources such as waste water may become economically feasible at price levels of US$ per ton.

Current phosphate reserves

Since phosphate rock is the only primary source of phosphate in the world and since no significant phosphate stocks are kept, the production and reserve figures of phosphate rock give a fair impression of the phosphate reserve situation in the world and its consumption. World reserves of phosphate rock, i.e. measured reserves were estimated at 15000 Mt in 2008 with a reserve base of 47000 Mt of phosphate rock (USGS, 2009). Roughly 80% of the phosphate rock reserves are accounted for by sedimentary phosphates. The remainder consists of igneous phosphates. The reserves of guano type deposits are negligible.

As can be seen in Table 2.2, China, Morocco and the US are by far the largest producers of phosphate rock. Both the US and China consume all or most of their own domestic production, which makes Morocco the chief exporter of phosphate rock and phosphate products in the world. The main producers of igneous phosphates are Russia, South Africa, Finland, Brazil and Canada.

Together with mine production, both the reserves and the reserve base of phosphate rock have increased over the past 15 years (Figure 2.1). After fluctuating between 125 and 145 Mt until 2006, mine production increased again to 167 Mt in 2008. Over the same period, reserves of phosphate rock increased from 11000 Mt to 18000 Mt in 2006 and then recently dropped to 15000 Mt. The reserve base increased from 34000 Mt to 50000 Mt and then dropped to 47000 Mt (Figure 2.1).

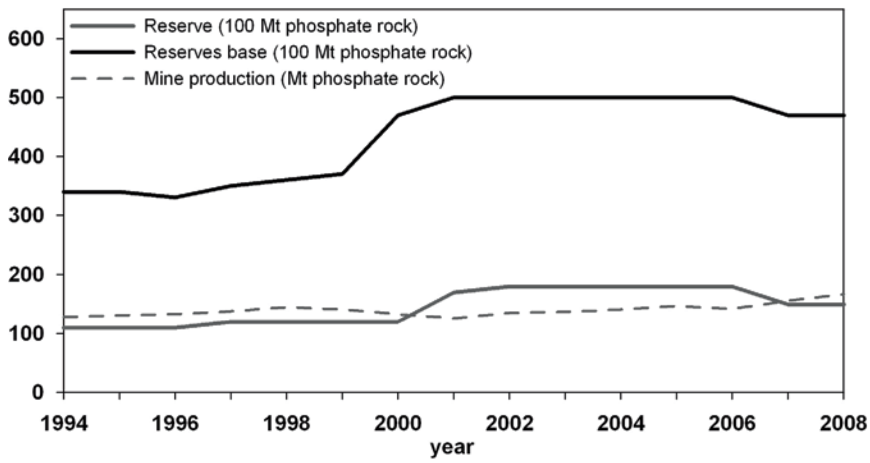
The recent increase in phosphate prices, which is reviewed in Chapter 3, has not yet resulted in an increased reserve and reserve base. This is because these reserves depend on long-term price developments and not so much on spot prices. Moreover, evaluation of new reserves requires some time causing a lag between price development and the size of the reserves.

The reserve supply period -which is the number of years that the supply of phosphate can continue at the present level- rose from 86 years in 1994 to 135 years in 2001 and then recently fell back to 90 years, the sharpest drop occurring in 2007. The reserve base supply period rose from 266 to 397 years in 2001 and dropped to 281 years in 2008. Due to the recent price increase, which will result in an increased reserve base, the reserve base supply period is also expected to increase in the near future.

Table 2.2:
Phosphate rock production in 2007 and 2008, and reserves and reserve base in 2008 (USGS, 2009). Note: Reserve has the unit x 100 Mt RP while production has the unit Mt RP (year)-1.

Country	**Mine production (Kt)**		**Reserves (Mt)**	**Reserve base (Mt)**
	2007	**2008**		
China	45 500	50 000	4 100	10 000
United States	29 700	30 900	1 200	3 400
Morocco and Western Sahara	27 000	28 000	5 700	21 000
Russia	11 000	11 000	200	1 000
Tunisia	7 800	7 800	100	600
Brazil	6 000	6 000	260	370
Jordan	5 540	5 500	900	1 700
Syria	3 700	3 700	100	800
Israel	3 100	3 100	180	800
South Africa	2 560	2 400	1 500	2 500
Australia	2 200	2 300	82	1 200
Egypt	2 200	3 000	100	760
Togo	800	800	30	60
Canada	700	800	25	200
Senegal	600	600	50	160
Other countries	8 110	10 800	890	2 200
World Total	156 000	167 000	15 000	47 000

Figure 2.1:
World production, reserves and reserve base of phosphate rock over the period 1994 - 2008 (USGS, 2007; USGS, 2009). Reserve has the unit x 100 Mt RP while production has the unit Mt RP (year)-1.



2.3 Resource development

To date, more than 1600 phosphate deposits have been identified worldwide. Only a small part of the resources in these deposits have been determined and an even smaller part has been entered into the indicated and measured reserve category at prices in the range of 25 to 40 US$ per ton. At the current price levels in the range of 50 to 100 US$ per ton (see e.g. USGS, 2008), the reserve and reserve base substantially increase. Not only will sub-economic resources suddenly become exploitable but also a new category of phosphate reserves - the intermediate grade underground deposits - will become available.

At present, 75% of the world's phosphate rock is produced from open pit mining. Underground mining is only feasible from high or special grade reserves. However, with prices ranging from 50 to 100 US$/ton, underground mining will become economically much more attractive and will add to existing reserves. At a production cost of up to 90 US$ per ton the then available reserve base would be sufficient for 240 years' consumption under a moderate consumption growth scenario (FAO/IFA, 1999).

As a response to the recent price developments, phosphate exploration has already picked up. Both land-based and marine resources have become the subject of exploration activities and development studies. As an example, Oklo Uranium Ltd has been granted an 8000 km2 permit for exploration in Mali, covering its Tatteul Phosphate Project. The area contains some 185 km2 of contiguous outcrop of phosphate bearing sedimentary rock (shale). Grades vary from 18 to 31% P_2O_5 and a thickness ranging from 0.5 to 2.2 metres (Oklo Uranium Ltd., 2008).

European phosphate deposits, such as the phosphatic chalk of the Mons Basin in Belgium and the Paris Basin in France – with grades in the order of 7 to 15% P_2O_5 - may also become of interest at higher prices. Attainable resources in Belgium are estimated at 60 Mt (Geochem Research, 1994). Also in Spain, substantial resources with P_2O_5 contents in the order of 13 - 19% are available in the Central Iberian Zone.

Large resources are also available on the continental shelf and on sea mounts in the Atlantic and Pacific Oceans (phosphorite nodules). Although phosphate prices are still too low to mine phosphate in the deep oceans, resources on the continental shelves are currently being evaluated. For example, the Bonaparte Diamond Mines company is shifting towards the development of prospective marine phosphate deposits in Namibia. Although the project is currently at the sampling stage, plans are to mine 40 - 50 million tons of unconsolidated sediment with a grade of 10 - 25% P_2O_5 in order to produce 3 million tons of commercial 35% grade P_2O_5 per year (Burger, 2008). The total resource in the upper 10 cm of the sediments on the Namibian shelf is estimated at 3020 Mt of ore albeit of a much lower grade (Notholt et al., 2005).

An update and even a rough estimate of the total global potential of these already discovered resources would require a substantial amount of work, not to mention the 'guesstimate' of hypothetical resources in presently undiscovered deposits. No doubt this work, which until recently has been neglected because of the low phosphate prices, will need considerable effort in the near future. Nevertheless, it is clear that at the current phosphate prices of 50 to 100 US$ per ton, tens of billions of tons could be added to our phosphate reserve base.

3. Global use and consumption of phosphate

3.1 Current use of inorganic phosphate

Inorganic phosphate is used in many different products and half-products. The most recent and complete overview of the global use of inorganic phosphate is given by Villalba et al. (2008). According to their study, 18.9 mln tons of phosphorus (P) entered the world economy in 2004. This amounts to 43 mln tons of P_2O_5, or roughly 143 mln tonnes of phosphate rock (assuming 30 wt% P_2O_5).

After beneficiation, phosphate rock is used for the production of: (1) fertilisers: 74% ; (2) industrial phosphates (e.g. feed additives and detergents): 7%, and (3) other uses: 10%. The remainder (9%) is lost in transportation and handling. The share of inorganic phosphate used as fertilisers, particularly produced through wet phosphoric acid, is by far the largest and will expand further as the global demand for food continues to increase (Villalba et al., 2008; Cordell et al., 2009). Table 3.1 lists the major phosphate fertilisers that are derived from the chemical processing of phosphate rock.

Industrial phosphates include animal feed additives, pesticides, and red phosphorus which is used for the production of flame retardants, fireworks, semiconductors and matches. Other industrial uses are in the food industry and in household applications, for example:

- phosphoric acid for pH control in soft drinks;
- sodium phosphate in the meat and fish industry;
- sodium pyrophosphate in baking mixes and potato processing;

- phosphate compounds in detergents and cleaning agents;
- phosphate compounds in toothpaste.

These industrial applications are marginal to insignificant in determining the need for phosphate rock in the near future, which is mainly driven by global food and biofuel production.

Table 3.1: Overview of major phosphate fertilisers. DAP, MAP and TSP are the most commonly used fertilisers. Source: Smil, 2000; Villalba et al., 2008.

Compound	**Acronym**	**Formula**
Diammonium phosphate	DAP	$(NH_4)_2.HPO_4$
Monoammonium phosphate	MAP	$NH_4H_2PO_4$
Triple superphosphate (concentrated superphosphate)	TSP	$Ca(H_2PO_4)_2$
Rock phosphate	RP	Apatite $(C_{10}(PO_4)6F_2$
Single superphosphate	SSP	$Ca(H_2PO_4)_2$
Dicalcium phosphate	DCP	$CaHPO_4.2H_2O$
Monopotassium phosphate	MKP	KH_2PO_4
Nitric phosphate and other N-containing phosphate fertilisers	often mixtures of DAP and other fertilisers	

The acronym MAP is often used for Magnesium Ammonium Phosphate (struvite).

3.2 Global fertiliser consumption

The gross national phosphorus balances are available for most of the OECD countries: http://stats.oecd.org/Index.aspx. As we saw in the previous section, phosphate can be found in many different products and half-products, and administration of the net consumption per country is not available. A fair impression of the *inorganic* phosphate consumption per country can be obtained by using the FAO fertiliser statistics (see FAO, 2009). After all, fertilisers represent, on average, 74% of the total annual phosphate production in the world. The top 30 fertiliser consumers are listed in Table 3.2.

The data presented in Table 3.2 gives a rough indication of the fertiliser consumption in 2005. However, it should be stressed that the administrative data presented by the FAO is surrounded by considerable uncertainty and the figures presented in Table 3.2 should be interpreted with caution. Comparison of the data presented in Table 3.2 with the global fertiliser statistics presented by the IFA (IFA, 2009) for 2005 reveal differences ranging from 0 to 36% (consumption data). FAO presents the state of the art statistics. For many countries data on non-fertiliser use are lacking and are therefore assumed to be zero.

This means that the data follow the assumptions:
- Non-fertiliser use assumed to be zero in the absence of data;
- Stocks of fertiliser assumed to be zero or stable;
- Country imports or exports of fertiliser data not available and assumed to be zero.

Country	Consumption	Production	Import	Export	Per capita consumption
	ton P_2O_5	ton P_2O_5	ton P_2O_5	ton P_2O_5	kg P_2O_5/ca
China	11 473 471	10 439 612	1 518 075	484 216	8.8
United States	6 409 635	10 890 000	596 156	4 160 287	21.7
India	5 226 434	4 092 561	1 144 742	10 869	4.8
Brazil	2 638 656	1 721 172	1 315 782	127 730	14.0
Australia	1 139 235	596 768	696 778	154 311	56.3
Pakistan	860 133	343 938	662 135	7 559	5.3
Turkey	782 711	365 258	432 797	15 344	10.8
Indonesia	762 868	468 478	297 073	2 683	3.3
Canada	693 121	278 028	477 989	62 896	21.4
Japan	687 879	329 667	362 329	4 116	5.4
France	597 000	158 402	515 652	77 054	9.5
Argentina	561 371	0	563 052	1 682	14.3
Vietnam	530 104	249 038	283 203	2 137	6.4
Iran	492 681	169 486	323 195	0	7.6
New Zealand	472 838	339 157	134 107	425	116.8
Spain	454 957	331 040	246 041	29 077	11.3
Mexico	433 907	79 555	364 501	10 150	4.1
Russia	346 840	2 586 575	2 005	2 241 741	2.4
Poland	327 668	435 333	44 127	151 792	8.5
Thailand	322 044	57 150	295 696	30 803	5.0
Italy	281 803	23 000	289 262	26 017	4.9
Germany	273 937	144 705	140 998	11 767	3.3
Bangladesh	262 114	69 022	193 092	0	1.8
Egypt	258 157	310 080	1 913	53 836	3.3
South Korea	246 791	69 545	24 554	113 560	5.1
United Kingdom	245 140	164 500	196 540	0	4.1
South Africa	212 315	313 462	33 950	135 097	4.5
Syria	182 357	127 818	54 540	1	9.9
Bulgaria	175 946	173 100	2 982	135	23.6
Chile	160 882	0	160 882	0	10.1

Table 3.2:
The 30 principal consumers of inorganic phosphate fertilisers in 2005 (FAO 2009, version April 2009).
Source: FAO, 2009 version April 2009, per capita consumption is calculated using USCB, 2009.

Note:
The FAO database was updated on 13 July 2009, when consumption figures for the Netherlands suddenly tripled to ~146 739 t P2O5 compared with the April 2009 version presented in Table 3.2 (51 579 t P2O5). Apparently FAO has included Non fertiliser use in their data on the Netherlands in 2009. Since the values for the Netherlands in the April 2009 version agree much better with the estimates from the IFA (43 000 t P2O5) and CBS (48 100 t P2O5) for 2005, the April 2009 version is presented here.

Apparently FAO has included Non fertiliser use in their data on the Netherlands in 2009. Please note that FAO has changed their calculation of P consumption and is working on an update. For the Netherlands data are available on non-P-fertiliser use but not for other countries. Therefore FAO can refine the calculation for the Netherlands.

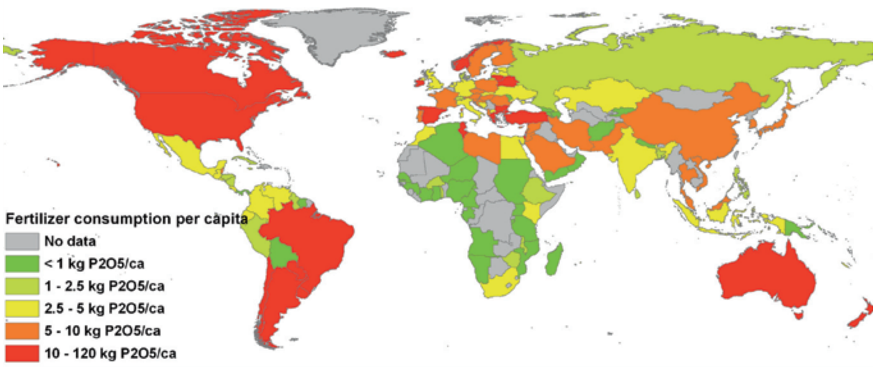


Figure 3.1:
Global overview of the per capita consumption of P2O5 in mineral fertiliser in 2005.
Source: FAO, 2009; USCB, 2009).
Fertiliser consumption on average represents 74% of the net inorganic phosphate consumption, but this varies from country to country.

As Table 3.2 shows, the largest consumers of phosphate fertilisers include the countries with a large agricultural sector such as China, the US and India. China and India do not export substantial amounts of food – which is mainly used for internal consumption (see e.g. FAO, 2009b) -, and the fertiliser statistics reflect the total net consumption of phosphate in these countries.

On a per capita basis, fertiliser consumption is highest in New Zealand and Australia (117 and 56 kg P_2O_5 per capita respectively). Like the US, these countries have a substantial agricultural sector and export a considerable amount of the food they produce (see e.g. FAO, 2009b). At the lower end of the spectrum are the developing countries with a consumption of less than 1 kg P_2O_5 per capita. Figure 3.1 presents the latter figures in a more illustrative way. In particular, the backlog in the African world is striking in spite of the fact that this continent hosts the largest reserves of phosphate rock in the world. Although this does not necessarily apply to all countries, the prevalence of malnourishment among the population is generally the highest in countries with the lowest fertiliser consumption (<1 kg P_2O_5 per capita).

Fertiliser consumption in the Netherlands in 2005 was much lower and amounted to some 51 000 t (CBS, 2009a), with a per capita consumption of 3.1 kg P_2O_5. However, as will be explained in section 5.1, the consumption of imported animal feed plays a much more important role in the phosphate budget of the Netherlands. Using our net total phosphate consumption in 2005 – i.e. including animal feed, feed additives and other commodities -, per capita consumption would amount to some 11 kg P_2O_5 per capita in 2005. As such, the fertiliser statistics presented in Table 3.2 do not always reflect a country's overall phosphate consumption.

3.3 Historical trends of phosphate consumption and prices

In the last 100 years, the global mine production of phosphate rock increased from 3.2 Mt/year in 1900 to 163 Mt/year in 2008, which amounts to an average increase of 3.4% per year (Figure 3.2). As far as we are aware there is no significant stockpiling of phosphate and consequently the production and consumption of phosphate show similar patterns.

The strongest increase in phosphate production – and hence consumption - occurred during the period from 1945 to 1988, when annual growth reached an average of over 7% per year. During the early 1990s, the production of rock phosphate suddenly collapsed to a pre-1980 level of 120 Mt/year, the cause of which was most likely new environmental regulations to prevent the over-application of phosphate on agricultural soils in western Europe and the US. Also, the collapse of the former Eastern Bloc caused a stop to all national

grant aids. Over a decade P was essentially not used in these countries. Next, developing countries (DC) lacked financial resources to invest in P fertiliser.
Since 2000, production has increased to 163 Mt of phosphate rock in 2008, which is probably the result of increased fertiliser consumption in rising economies such as China and India.

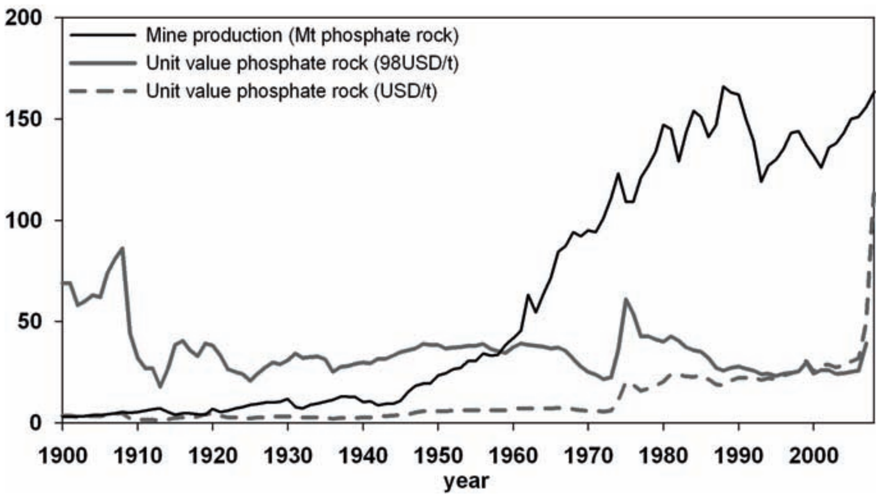


Figure 3.2:
Global phosphate production and price development of phosphate rock over the period 1900 to 2008. Prices reflect US$ import prices in real and constant 1998 US$ per metric ton phosphate rock.
Source: USGS, 2007; USGS, 2009.

Constant 1998 US$ prices for phosphate rock show – apart from some rapid fluctuations - a slightly negative trend over the period 1900 – 2000. During the same period, uncorrected US$ prices have gradually increased, with a small jump in the mid nineteen-seventies (see Figure 3.2). Only during the last two to three years have uncorrected phosphate prices picked up and increased from ~30 US$/ton in 2005 to 113 US$/ton in 2008 (USGS, 2009). However, the figures quoted are strongly influenced by the prices of long-term contracts and actual spot prices must have been substantially higher. P fertiliser prices have become unstable:
Prices increased from 2007 onwards, peaked in 2008 followed by a decline to the price level of 2007 and are currently (June 2010) again increasing. In fact, the USGS reported ‘a dramatic jump’ in the spot prices of phosphate rock approaching 500 US$/ton in 2008 (USGS, 2009). Such unrealistic spot prices are not representative of the long-term price developments in the phosphate market.

According to the Fertiliser Institute in Washington, price increases were caused by higher energy prices, shipping costs and a sharp rise in worldwide fertiliser demand (IFA, 2008). Furthermore, conventional phosphate reserves in the US are also slowly running out without being replaced by new resources. In combination with very high oil prices in 2008, this might have caused a panic-driven price development on the global phosphate market.

Other important factors are the devaluation of the US dollar, the tight supply and, possibly, a lack of long term investment in the phosphate industry because of the negative price developments in the last two decades. The tight supply conditions are expected to last until 2012 when new mines are projected to open in Australia, Brazil, Peru and Saudi Arabia (USGS, 2008).

4. Future trends of phosphate consumption and sufficiency of resources

4.1 Global drivers of the phosphate market

Determining future phosphate consumption and hence the sufficiency of current phosphate reserves, requires a proper understanding of the drivers of the phosphate market and future developments. The most important use of primary phosphate is for food production (fertilisers, and to a lesser extent feed and food additives). And the increasing demand for food will lead to a growing demand for phosphate. Moreover, higher standards of living, with a concomitant increase in meat consumption, will lead to a further increase in global phosphate demand. More recently, the production of biofuels has also started to play a role in global fertiliser consumption. The most important drivers of the phosphate market in the long term are therefore:

- the growing world population;
- the increasing standards of living and meat consumption;
- the increasing production of biofuels in relation to oil prices.

To keep up with future phosphate demand, mining companies will have to increase their production capacity and invest in the future exploitation of new resources. Although there are indications that mining companies have not made sufficient investments in the past, which currently leads to tight supply conditions, this will be a temporary effect as increasing phosphate prices will spur the exploitation of currently uneconomical phosphate resources. Higher phosphate prices of 50 - 100 US$/ton will however persist in the long term due to decreasing grades of the phosphate ores and subsequent higher production costs. Although elevated phosphate prices could lead to somewhat depressed demand, this effect is difficult to quantify.

In addition to higher phosphate prices, other factors that could slow down the growing demand for phosphate include: 1) a slowing down of the world economy and consumption, and 2) legislation to reduce nutrient application in agriculture. Although the world economy has currently slowed down, leading to reduced consumption in some sectors, it is unlikely that this pattern will persist in the longer run. The current economic crisis will, as such, not affect the increasing global demand for phosphate in the future. In contrast, legislative measures to reduce the amount of fertilisers and manure used on agricultural land will have a permanent effect on phosphate consumption. The question is whether these reductions in European countries will weigh up against the increasing demand in countries such as China and India.

4.2 Future trends of phosphate consumption

It is clear from the previous section that global phosphate consumption is likely to grow in the future despite higher phosphate prices and the current economic downturn. The growth rate will, however, be different for different regions. Whereas phosphate consumption in Europe might decrease, consumption will increase in countries such as India and in SE Asia. The US, Brazil and some European countries might also step up their phosphate consumption, mainly to increase their biofuel production.

This section reviews and discusses various scenarios for the growth of global phosphate consumption. A distinction is made between the growth of the global phosphate consumption with and without the effects of biofuel production.

Global consumption

The world population is currently growing at a rate of 1.5% per year. The United Nations expects the world population to reach 9 billion in 2050, which is a 50% increase on the current 6 billion (UN, 2005). It is likely that the growth rate will level off around 2050 and the population will then remain stable or show only slight growth. Assuming that food consumption and agricultural production will keep pace with population growth, we may - as a first approximation - expect a similar growth rate for global phosphate consumption.

For the short to medium term i.e. the next few years, the IFA predicts phosphate consumption will grow annually by 2.7%, which is somewhat higher than the world population growth (IFA, 2008). However, looking at phosphate consumption in the past half century, the growth rate estimated by the IFA may even be conservative: between 1950 and 2000, the world population grew by about 1.4%, but the production of phosphate rock rose by 4.4% on an annual basis.

This discrepancy is probably the result of the improved standard of living and higher meat consumption, particularly in the western world.

Since the production of a meat-based diet uses about 3 times more phosphate than the production of a vegetarian diet (e.g. Cordell et al., 2009), phosphate consumption may increase at a substantially faster rate than the population if countries such as India, China and Brazil continue to develop to North American or European food consumption standards in the future. The use of phytase in animal fodder may make the uptake of phosphate by domestic animals more effective.

Consumption for biofuel production

When we take into account the increasing amount of phosphate required for the production of biofuels such as bio-ethanol and bio-diesel, the IFA growth figures given above might be an underestimate. Crops grown for the production of biofuels currently account for 2.4% of the world fertiliser consumption (IFA, 2008). This means that the consumption of phosphate for biofuel production in 2008 required some 3 - 4 Mt of phosphate rock.

The biofuel produced globally in 2008 represents an energy value of about 1 eJ (exajoule). Depending on land availability and production capacity, the energy derived from biofuels is estimated to have increased in 2050 to anywhere between a low of 160 and a high of 450 exajoules (Table 3.3). This would imply a growth of the phosphate consumption of 12.3% to 15.7% under low and high biofuel growth scenarios respectively. Biofuel production from organic waste and residues are not included here as they do not require additional phosphate i.e. this growth is included in global consumption figures. These estimates also exclude the production of biomaterials such as plastics from bio-ethanol and bio-diesel.

Serious competition between phosphate consumption for biofuel and food production will however result in political measures to restrain the production of biofuels from both existing agricultural land as well as marginal lands. Therefore, the additional role of biofuel production remains difficult to predict. Although it is clear that the amount of phosphate used for biofuel production will grow rapidly in the next two decades, it is difficult to determine what growth rates can be expected after 2030 - 2040. In the following section, zero growth for the period after 2030 is assumed. A shift from land-based biofuel crops to the farming of marine algae for biofuel production will eliminate the competition with food production, but will probably not substantially change the phosphate requirements. Sometimes it is argued that because algae use P more efficiently, the phosphate requirements will decrease.

Biomass type	**Low scenario**	**High scenario**
Energy crop farming (current agricultural land)	100	300
Energy crop farming (marginal land)	60	150
Marine energy crops	?	?
Totals	**160**	**450**

Table 4.1:
Future energy production from selected biomass types in 2050 (all in exajoules = 1018 Joules; WWI, 2006). The data represents the more conservative estimate by WWI, and excludes the production of biofuels for biomaterials and biofuel production from waste and residues (e.g. plastics).

4.3 Future scenarios

Different scenarios can be described by combining the figures for the global population and wealth growth and the additional growth due to biofuel production as mentioned in the previous section. The following four scenarios are evaluated concerning the sufficiency of current phosphate resources:

- **Scenario 1 (zero growth):** zero growth of global food consumption and biofuel production.
- **Scenario 2 (low growth):** 1.5% annual growth of global food consumption until 2050 and 12.3% annual growth of biofuel production until 2030.
- **Scenario 3 (intermediate growth):** 2.7% annual growth of global food consumption until 2050 and 12.3% annual growth of biofuel production until 2030.
- **Scenario 4 (high growth):** 4.4% annual growth of global food consumption until 2050 and 15.7% annual growth of biofuel production until 2030.

The sufficiency of the global phosphate reserve base under different scenarios is plotted for the period 2008 – 2100 (Figure 4.1). It is clear that the different scenarios result in very different predictions for the time the current phosphate reserves will be exhausted, which ranges between 2042 and 2098 (Table 4.2). These estimates fall within predicted sufficiency of the phosphate reserves of 50 – 100 years as calculated in earlier studies (Steen, 1998; Smil, 2000; Gunther, 2005). The total reserve base would however last for much longer and predictions range between 2072 (high growth) and well beyond 2200 (zero growth).

In view of the slight growth of the world phosphate consumption in the past two decades, it is more likely that a scenario of low to moderate global growth will be realised (scenarios 1 or 2). Nevertheless, the combined production of food and biofuels under these scenarios will cause the global reserve base to be depleted roughly somewhere between 2100 and 2150 (Table 2).

The increasing demand for phosphate will spur exploration efforts for new reserves, which will add to our future reserve base. Although the size of the future reserve base is not known, it seems safe to state that at prices of 50 - 100 US$ per ton the reserve base would roughly double (see Chapter 2). If the future increase of the reserve base were taken into account, our global phosphate reserves would last well into the next century and probably well beyond. Previous projections by other authors (e.g. Steen, 1998; Smil, 2000; Gunther, 2005) often only take the current reserves into account, which is a gross underestimate of our global minable phosphate resources.

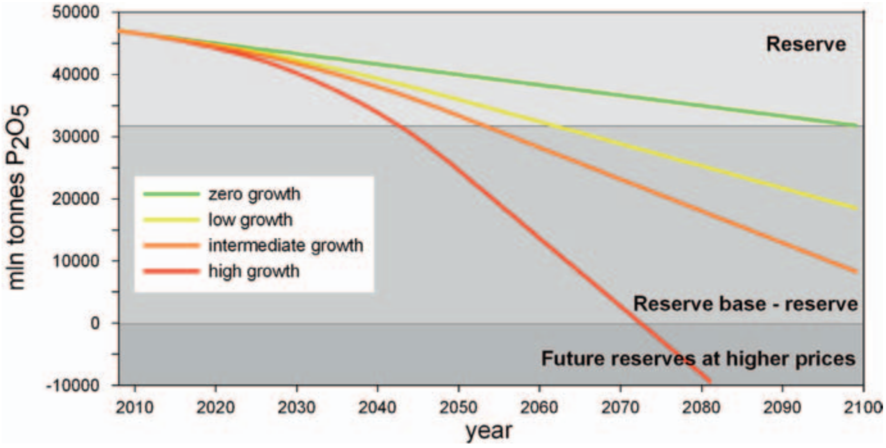


Figure 4.1:
Depletion of global phosphate reserves and reserve base (excluding reserves) under zero, low, intermediate and high growth scenarios (see text). The size of the future reserve base is not known as it largely depends on future phosphate prices.

Scenario	**Consumption in 2050 (Mt/y)**	**Year of depletion of reserves**	**Year of depletion of reserve base (incl. reserves)**
Zero growth	167	2098	>2200
Low growth	356	2061	2151
Intermediate growth	511	2050	2108
High growth	1093	2042	2072

Table 4.2:
Calculated phosphate rock consumption in 2050 and sufficiency of current reserves (15 000 M ton) and remaining reserve base (i.e. excluding the reserves; 32 000 M ton) under various growth scenarios (see text).

5. Phospate in the Netherlands

5.1 Import, export and consumption

The Netherlands does not have any economically-viable phosphate resources and is therefore dependent on the import of phosphate from abroad. Local occurrences of phosphorite nodules in upper Miocene sediments near Ootmarsum and at some depth in Zeeland are not commercially viable. In 2005, the total import of phosphate amounted to some 1.06 Mt P_2O_5, which includes both inorganic phosphate (e.g. rock phosphate, fertilisers and feed additives) as well as organic phosphate contained in food and animal feed (see Table 5.1). The bulk of the phosphate imported into the Netherlands is again exported in the form of fertilisers and inorganic chemicals (648 100 t P_2O_5), as food for human consumption (185 500 t P_2O_5) and to a lesser extent as animal feed and manure (43 500 t P_2O_5). In total, some 83% of the phosphate that entered the Netherlands in 2005 was again exported in some form. A more detailed overview of the import, export and consumption of phosphate is presented in Annex I.

In 2005 the phosphate balance of the Netherlands amounted to 183 300 t P_2O_5 (Table 5.1), which amounts to per capita consumption of some 11 kg P_2O_5. The actual agricultural phosphate consumption -which includes the phosphate in agricultural export commodities such as food and animal feed - is somewhat higher (208 500 t P_2O_5; see Annex I). The phosphate used for agricultural production is primarily imported as animal feed (142 100 t P_2O_5), whereas the remaining phosphate is from fertilisers (48 100 t P_2O_5), feed additives (16 000 t P_2O_5) and other forms (2 300 t P_2O_5).

The bulk of the total net consumption of phosphate in the Netherlands is not so much related to consumption of phosphate fertilisers, but to the import of animal feed. This is typical for a few countries, including the Netherlands, Belgium and Denmark, that produce huge quantities of meat, poultry and dairy produce relative to the amount of agricultural land available. These countries are dependent on the import of substantial amounts of animal feed from abroad to feed their livestock and poultry.

Total agricultural production in the Netherlands (i.e. in crops, animal products, animal feed and surplus manure) represents some 123 700 t P_2O_5 in 2005. Taking the export of food (16 000 t P_2O_5), animal feed and surplus manure (43 500 t P_2O_5) into account, it is calculated that the phosphate used for the production of food for domestic consumption amounts to some 64 200 t P_2O_5. Besides the phosphate used for agricultural production, on balance around 34 400 t P_2O_5 is used for other purposes including detergents, food additives, fireworks etc. (Table 5.2). Detailed information on the import and export of these commodities is available for the Netherlands on CBS statline (http://statline.cbs.nl/statweb/).

The phosphate consumed in 2005 accumulated in various natural compartments including agricultural and non-agricultural soils as well as surface water (see Annex I). Most of the phosphate accumulated in the top layer of agricultural soils (77 900 t P_2O_5) and other soils including gardens, parks, roadsides and allotments (39 000 t P_2O_5). The largest sink of phosphate in the Netherlands is the agricultural soils, where on average 40% of all phosphate consumed accumulates as less available forms of phosphate. The accumulation of phosphate in these soils is discussed in more detail in section 5.4.

A small fraction accumulates in surface water, which is a result of phosphate run-off from agricultural land as well as phosphate discharged to the surface water by waste water treatment plants. A part of this is again removed by dredging. On balance 9 2000 t P_2O_5 accumulated in the surface water compartment in 2005 (see Annex I). Furthermore, there were no losses from the surface water compartment to the major rivers and North Sea (Annex I)

Table 5.1: Overview of the import, export and net consumption of phosphate in the Netherlands in 2005 (from CBS/Statline, 2009a). See also Annex I.

Import	**tons P_2O_5**	**Export**	**tons P_2O_5**	**Balance**	**tons P_2O_5**
Food	169 600	Food	185 600	Net food export	-16 000
Animal feed	142 100	Animal feed & Manure	43 500	Net consumption of animal feed	98 600
Phosphate rock, fertilisers & other	748 300	Phosphate rock, fertilisers & other	648 100	Net consumption of fertilisers & other	100 200
TOTAL	1060 000	TOTAL	877 100	TOTAL	182 900

The remaining fraction of the phosphate consumption in 2005 (57 300 t P_2O_5) accumulated in the solid waste compartment – both as organic and inorganic waste -, as well as in other commodities (see Annex I). During waste water treatment, the bulk of the phosphate is removed from the influent and transferred into the solid waste stream (sewage sludge; 27 000 t P_2O_5; CBS, 2008). Taking the contribution from sewage sludge into account, it is calculated that some 30 300 t P_2O_5 is present in the remaining solid waste as well as in other commodities.

The data presented in Table 5.1 and Annex I are based on administrative data from different sources in combination with various assumptions made by Statistics Netherlands (CBS). Information about the uncertainty in these calculations, or the assumptions made, is however not provided. Apart from the agricultural phosphate cycle, which is well described, the data otherwise have a limited level of detail. It is for example unclear how much of the phosphate present in raw agricultural products is finally consumed as food by the Dutch population, and how much is lost as organic waste during processing.

Table 5.2 : Estimates of the amount of phosphate present in various items in 2005. See also Annex I.

Item	**ton P_2O_5**	**Remark**
Inorganic phosphate including detergents, food additives, etc.	34400	Calculated as the difference between the net inorganic phosphate consumption (100 800 t P_2O_5) minus agricultural consumption of fertilisers (48 100 t P_2O_5), feed additives and others (18 300 t P_2O_5).
Organic waste during primary processing, transportation and storage of food	19000 – 32000	It is estimated that 30 to 50% of the raw food produced in the Netherlands is lost during production, transportation and storage (LNV, 2009). The amount of phosphate in the waste is calculated using net amount of phosphate in food (64000 t P_2O_5).
Food consumption by the population (incl. losses)	32000 - 45000	The lower and upper values are calculated as the remainder from the net amount of food (64000 t P_2O_5) and a 30 to 50% loss during primary production, transportation and storage.
Total phosphate in liquid waste stream / waste water	33000 (19600 from food consumption; remaining 10700 from other sources)	Source: CBS, 2008. The average dietary intake amounts to 1.1 P_2O_5 kg/year (Reiman and Caritat, 1998). With a total population of 16.2 million inhabitants and a 10% loss during food preparation and storage (LNV, 2008), the dietary intake would amount to 19 600 t P_2O_5. The remaining 10700 t P_2O_5 must be derived from other sources such as detergents, primary processing of food (washing) and other sources.

Table 5.2 shows the amount of phosphate present in some of the missing items, which are based on additional data sources and/or various assumptions. This overview is not exhaustive and excludes phosphate recycling (see section 5.4). Phosphate losses in the Netherlands are further reviewed in section 6.1.

5.2 Historical trends

Administrative data on the consumption of phosphate in the Netherlands is only available for the period 1985 – 2008 (Figure 5.2), when phosphate consumption in the country declined substantially from 332 000 t P_2O_5 in 1985 to 177 000 t P_2O_5 in 2005. This reduction was largely driven by a decreasing consumption of inorganic phosphate commodities such as feed additives and detergents (> 50%) and phosphate fertiliser (> 40%). The decreasing overall trend is further accelerated due to the decreasing consumption of animal feed (Figure 5.1).

The decreased consumption of inorganic phosphate (excluding phosphate fertilisers) - from 119 000 t P_2O_5 in 1985 to 50 000 t P_2O_5 in 2005 – was caused, at least in part, by a decreased consumption of feed additives. Substantially fewer feed additives were needed following the introduction of phytase in animal feed, which increases the uptake of phosphate from feed (Schoumans et al., 2008b). Next, standards for P requirement of animals were lowered. For instance for dairy cattle the guide line for the P content of grass was lowered from 4 to 3.5 g/kg dry matter. As a consequence, the need to import large quantities of animal feed also decreased (Figure 5.1). A reduction of phosphate in detergents to prevent eutrophication of surface waters could further explain the decreasing consumption of inorganic phosphate since 1985. Compared to 1985 industry and communities were able to lower P input in freshwater streams in 2000 with 75-89% while agriculture lowered only 12%.

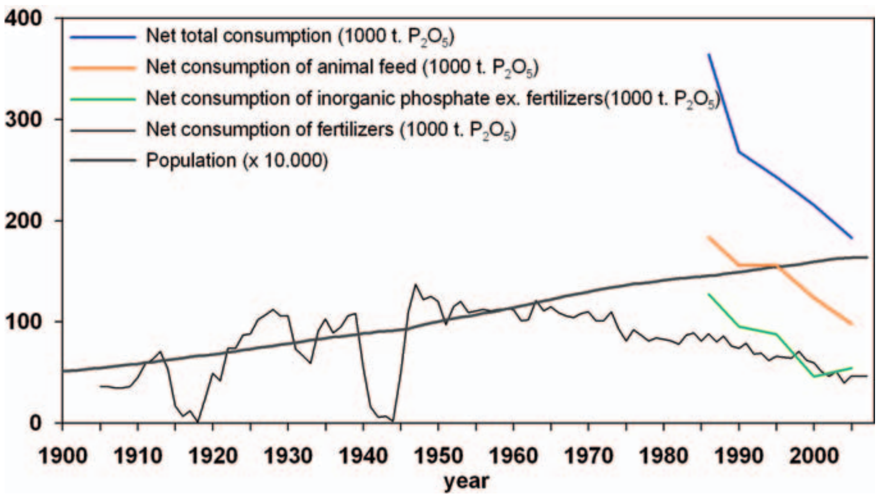


Figure 5.1: Historical trend of phosphate consumption in the Netherlands in the last century (total net consumption, net import of animal feed, net consumption of inorganic phosphate excluding fertilisers, and net consumption of fertilisers). Historical trend of the Dutch population shown in grey (Sources: CBS, 2001; CBS, 2009a).

The consumption of phosphate fertilisers has been declining since it peaked just after the Second World War (Figure 5.1), when much of the existing agricultural land was probably nutrient deficient and required substantial fertilisation to improve crop yield. And because livestock numbers were low, the animals did not produce enough manure to meet the nutrient requirements. Moreover, just after WOII manure was not valued for phosphorus. Only the last 15 odd years farmers take P from manure fully into account. Fertiliser consumption has gradually decreased since then.

The reason for this ongoing decline can be partly explained by the strong development of intensive livestock farming during the second half of the last century (e.g. CBS, 1999). The large surplus of P on the national balance forced the government to implement measures to reach a balance between input and output of P from manures and fertilisers. As a surplus leads to a penalty, farmers were forced to lower their P use. This was at the expense of P from fertilisers (Henkens and Van Keulen, 2001; Schroder et al, 2007).

5.3 Future trends

Future phosphate consumption trends will be largely driven by changes in agricultural practice, which represents the bulk of phosphate consumption in the Netherlands. In 2006, existing regulations for nutrient application were replaced by a new legislative framework, the Fertilisers Act 2006 (Meststoffenwet 2006), which requires Dutch farmers to further reduce nutrient application, which will result in a further decrease in phosphate consumption.

These regulations are mainly driven by European requirements with regard to nitrogen discharge from agricultural land to surface water and groundwater (Directive 91/676/EEC; see VROM, 2004, i.e. Nitrates Directive). The final goal of this directive is to reduce eutrophication and improve the ecology of surface water and groundwater. Eutrophication of surface and groundwater is still prevalent in large parts of Europe where agricultural activities are intensive (see e.g. EEA, 2009).

In this context it is however interesting to note that phosphate concentrations in many agricultural soils in western Europe are so high that even without any additional phosphate fertilisation a high crop yield can be achieved for several years (Van der Werff et al., 1995). It is also estimated that phosphate fertilisation is currently not necessary at all on 35% of the agricultural soils in the Netherlands as a result of a high degree of phosphate saturation in these soils (see MNP, 2007).

Although the situation in the Netherlands has significantly improved over the past few decades, nitrate concentrations in shallow groundwater in the sandy soils in the Netherlands generally do not meet the required EU level of 50 mg/L (Hooijboer et al., 2007; MNP, 2007). Furthermore, only 34% of the surface water monitoring locations met the maximum tolerable risk levels for nitrogen (2.2 mg/L), whereas 57% of the locations met the maximum tolerable risk levels for phosphate in 2005 (0.15 mg/L; MNP, 2007).

The Fertilisers Act defines quota for the maximum amount of fertiliser that can be applied to the soil (phosphate application standards). This quota applies to the sum of all forms of fertilisers and animal manures. Other than for nitrate, however, soil conditions and crop requirements are not taken into account for phosphorus other than the phosphate status. Three classes are distinguished: low, neutral and high. The application use standard at a high rating of the soil P status is lower than the offtake by the crop. A neutral rating receives crops offtake and at a low rating the phosphate application standard is higher than crop offtake. Furthermore, a distinction is made between for grassland and arable land including field production of vegetables (see Table 5.3).

For grassland and arable land the application of phosphate fertilisers has to be substantially decreased in the coming years to 2015. The objective of the quota is to reach a steady state fertilisation by 2015, which means that the amount of N and P fertilisers applied to the land match the amount of N and P extracted with the crops, plus an unavoidable loss of 5 kg P_2O_5 /ha (see VROM, 2004). It is assumed here that the steady-state fertilisation approach will not affect crop yield until at least 2030 (MNP, 2007).

Gradually reducing the amount of phosphate that can be applied to the land does not necessarily imply that all farmers have to cut back on their current fertiliser application: some 35% of the agricultural soils in the Netherlands do not need phosphate fertilisation as a result of a high degree of phosphate saturation (see e.g. MNP, 2007). As such, the actual reduction of fertiliser consumption as a result of these legislative measures cannot be directly translated to effective reduction of agricultural phosphate consumption in general.

The reduction measures also have a downside, as they lead to an excess of animal manure in some areas in the Netherlands. In 2006, the excess manure produced amounted to some 4 000 t P_2O_5, whereas in 2015 excess manure is estimated to amount to some 9 000 t P_2O_5 (Luesink et al., 2008). As such, a gradual reduction of livestock number – especially pigs – and poultry, should be considered in order to prevent an accumulation of excess manure, or manure should be digested more often and the phosphate recovered in mineral form.

Table 5.3:
Phosphate application standards for arable land and grassland during the period 2010-2015. The standards for 2014 and 2015 are indicative. The figures in brackets show the maximum quantity of phosphate from livestock than can be applied (Ministry of Agriculture, Nature and Food Safety, Fourth Action Programme Nitrate Directive (2010-2013).

	Third AP		Fourth AP				Fifth AP	
	2006	2009	2010	2011	2012	2013	2014	2015
Grassland								
Soils with high phosphate levels	110	100	90	90	85	85	85	80
Phosphate-neutral soils	110	100	95	95	95	95	95	90
Soils with low levels of phosphate	110	100	100	100	100	100	100	100
Arable land								
Soils with high phosphate levels	95 (85)	85	75	70	65	55	55	50
Phosphate-neutral soils	95 (85)	85	80	75	70	65	65	60
Soils with low levels of phosphate	95 (85)	85	85	85	85	85	80	75

5.4 Accumulation of phosphate in the soil compartment

For agricultural purposes, the buffering capacity and the total plant available P pool are important. The plant available phosphate fraction consists of the P in soil solution (i.e. < 0,5 kg phosphate/ha), the reversible bound P on hydroxides of aluminium and iron (i.e. ~ 600 kg phosphate/ha) and the quasi irreversible P pool (i.e. 2000+ kg phosphate/ha). Phosphate is taken up by the plant from soil solution, the reversible bound phosphorus acts as a buffer and replenish immediately phosphorus taken up by the plant. Quasi irreversible bound phosphate replenish phosphate at a lower rate (years). Next mineralisation of organic phosphate forms in soil enters inorganic phosphate that redistribute over soil solution and pools of sorbed phosphates. Because phosphate has a tendency to co-precipitate with various minerals and to adsorb on mineral surfaces, most of the phosphate is contained in mineral precipitate, partly decayed organic matter and adsorbed onto mineral surfaces, and will not be readily available (see e.g. FAO, 2008 or Schoumans et al., 2008).

Figure 5.2 shows the changes of the phosphate pool in the soil compartment over time. The total timescale covers several thousand years, but the rate at which changes occur depends on climatic conditions. Apatite is the primary phosphate mineral, which is slowly broken down by weathering, and transformed into a fixed and occluded phosphate pool (precipitates with iron and aluminium oxyhydroxides and precipitation of calcium phosphates), an absorbed phosphate pool (absorption by different clay minerals) and an organic phosphate pool. In particular, the phosphate in the fixed and occluded pool is hardly available for plants, whereas the phosphate in the absorbed pool, and to a lesser extent the organic pool, is more readily available for plants.

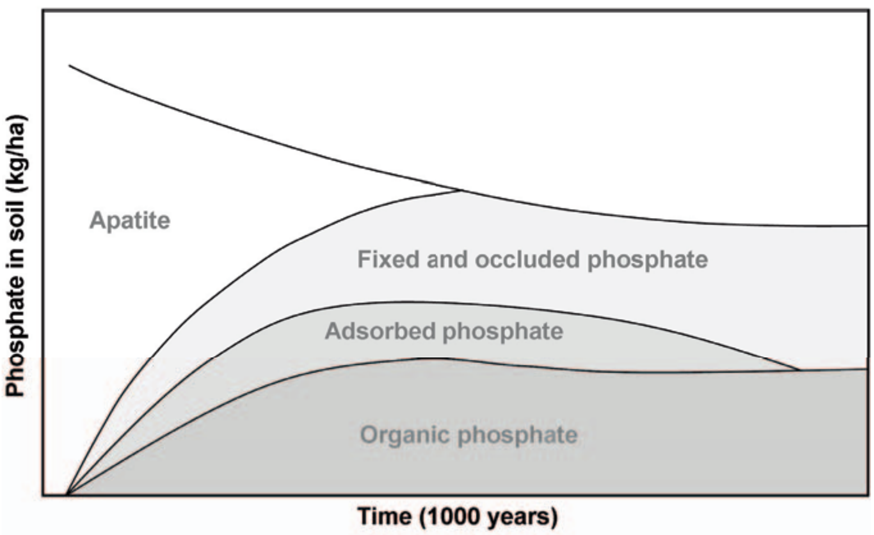


Figure 5.2:
Overview of changes of the natural phosphate pool in the soil compartment as a function of time. The total timescale covers several thousand years (after Walker and Syers, 1976).

As a result of the tendency of phosphate to precipitate and adsorb in the topsoil layer, only some 60% of the agricultural phosphate consumption in the Netherlands is effectively used for the production of crops, animal products and animal feed (123 700 t P_2O_5). The remaining 40% of the agricultural phosphate consumption accumulates in agricultural soils (77 900 t P_2O_5), or gets lost through surface run-off (6 900 t P_2O_5).

These figures represent average values for the Netherlands for 2005, and actual values vary from place to place depending on the type of agricultural practice and the local soil properties and topography. Nevertheless, these values reveal that substantial phosphate accumulation in the Dutch agricultural soils is still ongoing. Although a small part of the phosphate will have moved into the deeper soil layers, the bulk of this phosphate is still present in the upper soil layer (roughly the top 0 – 40 cm).

To give an idea of the total amount of phosphate present in Dutch agricultural soils, we used the density corrected relative enrichments from Van der Veer, 2006. These values represent the excess or surplus of P_2O_5 in the topsoil compared with the concentrations in the deeper, undisturbed soil layer (see Table 5.4). From this it is estimated that the top 20 cm of agricultural soils contain 1.9 Mt of P_2O_5 per ha, which excludes the phosphate that is naturally present in the different soil types. This phosphate is present in the fixed and occluded, adsorbed and organic phosphate pool (see Table 5.4). In a study of Reijnveld et al. (to be published) it is estimated that about 4500 kg P_2O_5/ha has been accumulated.

The calculation shows that the accumulated amount of phosphate in the topsoil layer is equal to ~40 years of the current inorganic phosphate fertiliser consumption (46 000 t P_2O_5/y in 2005). More data on the P surpluses from manure and fertilisers are available on: http://www.cbs.nl/nl-NL/menu/cijfers/statline/zelf-tabellen-maken/default.htm and http://www.pbl.nl/nl/dossiers/Mest_en_Ammoniak/feitenencijfers/index.html. The phosphate that is present below the plough layer, albeit a small amount, will however not be available for crops. Although a part of the accumulated phosphate fraction can become available for plants, the relevance of the accumulated phosphate fraction for agriculture greatly depends, among other things, on the local soil properties and the relative size of the different phosphate pools. Nevertheless, this offers opportunities to decrease application of phosphate fertilisers in the Netherlands without a substantial loss of crop yield.

Table 5.4:
Estimated total amount of accumulated P2O5 in the Dutch soils. Calculations based on a median P2O5 concentration in the subsoil of 0.27 wt% and a soil density of 1600 kg/m3 as used by Van der Veer (2006). The corrected enrichment is the relative density corrected enrichment as determined in different soil types (for details see Van der Veer, 2006).

Soil type	Enrich-ment (%)	Excess P_2O_5 (mg/kg)	Area (103 ha)	Volume (109 m3)	Mass (1000 Mt)	Accumulated P_2O_5 (1000 t)
Sand	253	0.070	984.0	2.00	3.15	865
Silt/clay	198	0.054	1,003.6	2.00	3.21	883
Peat	207	0.057	172.2	0.34	0.55	151
Total			2,159.8	4.30	6.91	1900

The application of nutrients such as phosphorus (P) and nitrogen (N) has significantly affected the quality of the environment through widespread eutrophication of aquatic and terrestrial ecosystems (e.g. Carton and Jarvis, 2001). This is however not the only reason to advocate more efficient fertiliser use in agriculture Most inorganic phosphate fertilisers such as triple-phosphate and diammonium phosphate contain rather high concentrations of cadmium[1] and other toxic metals, and subsequent fertiliser application has led to substantial accumulation of toxic metals such as cadmium in agricultural topsoils (e.g. Spijker, 2006, Van der Veer, 2005, Nziguheba and Smolders, 2008). Like phosphate, cadmium also has a tendency to accumulate in the topsoil layer. As a consequence, the concentrations of cadmium in Dutch agricultural topsoils are now two to three times higher compared with naturally prevailing concentrations (e.g. Spijker, 2006, Van der Veer, 2005). Farmers have to use P from animal manure more efficiently. This goes at the expense of P from fertilisers. However, the input of Cu and Zn becomes therefore higher than crops need. Cd can be a environmental issue but the risk declines due to a lower use.

1 *An overview of cadmium concentrations in different inorganic phosphate fertilisers can be found in Van der Veer (2005), MMF (2008) and Nziguheba and Smolders (2008).*

6. Phospate recycling and recommendations for sustainable use

Dutch Agriculture is highly intensive and productive. Until the mid 1980s growth in the agricultural sector in the Netherlands was one of the highest of the OECD countries (Oenema et al., 2005[2]). The side-effects of agricultural intensification (overproduction, eutrophication and damage to the environment) were incentives to change government policy (Henkens & Keulen, 2001[3], Oenema, 2004[4]). This policy focused on a more balanced use of nitrogen and phosphate, but not on phosphate recycling as such. However, the rapid depletion of available sources of minable phosphate presents a new incentive for government to review policy on this matter. The phosphate balance should take account of the already available and renewable sources of phosphate in the Netherlands. This chapter discusses the phosphate balance in the Netherlands, and the means to balance and recover phosphate.

6.1 Phosphate balance in the Netherlands

The sustainable use of phosphate requires an understanding of phosphate sources that can be re-used effectively. The allocation of these sources depends largely on the scale of the system under study and scales differ per country. For instance, the import of phosphate with feed concentrates or crops (plant products) is negligible in the national phosphorus balance of China (Ma et al., 2010[5]), whereas it is an important source for the Netherlands (CBS, 2010[6]). This chapter focuses on methods to recycle phosphate in the Netherlands on a national scale.

[2] *Oenema, O., L. van Liere & O.F. Schoumans, 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands. Journal of Hydrology 304: 289–301.*

[3] *Henkens, P.L.C.M., Van Keulen, H., 2001. Mineral policy in The Netherlands and nitrate policy within the European Community. Neth. J. Agric. Sci. 49, 117–134.*

[4] *Oenema, O., 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. J. Anim. Sci. 82, 1–11.*

[5] *Ma. L., W.Q. Ma, G.L. Velthof, F.H. Wang, W. Qin & F.S. Zhang, 2010. Modelling Nutrient Flows in the Food Chain of China. J. Environ. Qual. 39: 1-11.*

[6] *CBS StatLine, June 2010, http://statline.cbs.nl/StatWeb/?LA=en.*

National phosphate balance

Phosphate enters the Netherlands by transboundary rivers (Rhine, Meuse and Scheldt) and the northern delta of the Ems, as rock phosphates, other organic and inorganic sources, and together with imported food and animal feed. Phosphate in transboundary rivers is also exported again and effectively discharged into the North Sea. Rock phosphates, fertilisers and other organic and inorganic sources (including phosphoric acid), food including waste, animal feed and manures are also partially exported.

Although most (83.1%) of the phosphate entering the Netherlands leaves the country again, 183.2 Gg P_2O_5 (80 Gg P) – i.e. 16.9% of the annual input for 2005 – accumulated in the Netherlands (Table 6.1). Accumulated P is found in end products, residual P in (non) agricultural soils and in surface waters and sediments. Improving the national phosphate balance can be achieved by decreasing input and / or by increasing output.

Table 6.1: National phosphate balance in the Netherlands in 2005 in Gg P_2O_5. Source: CBS StatLine; June 2010, P_2O_5 = 2.29 x P.

Input	Transboundary rivers	22.9
	(In)organic compounds	748.8
	Food	169.5
	Animal feed	142.0
	Total input	1083.2
Output	Transboundary rivers	22.9
	(In)organic compounds	648.1
	Food including waste	185.5
	Animal feed and manures	43.5
	Total output	900.0
Accumulated	Final products	57.3
	Agricultural soils and ground water	77.9
	Non agricultural soils and groundwater	38.9
	Surface water and sediments	9.2
	Total accumulated	183.2

It is assumed that all phosphates imported in transboundary rivers are also exported again, so there is no net effect on the national P balance. The Netherlands cannot control the transportation of P in transboundary rivers; control requires coordinated multinational decisions taken by the countries along the Rhine, Meuse, and Scheldt river basins and the Ems delta. All four river basins are densely populated (100–450 inhabitants per km^2), industrialized and have intensively managed agriculture (Oenema et al., 2005). The countries in which these river basins are located must jointly implement effective measures to decrease phosphate loading into these river basins.

Food production in the Netherlands exceeds food import, so net phosphate export in food exceeds net phosphate import. Feed export levels are small compared with import levels, so much of the phosphate P in feed remains in the country. The P balance of feedstock is an essential part of the total agricultural phosphate balance in the Netherlands. The P balance of feedstock can be effectively lowered by reducing the net import of animal feed or, alternatively, by increasing the export of animal manure.

Agricultural phosphate balances

Figure 6.1 shows the agricultural phosphate balances. Both a sector balance and a soil balance are given. The sector balance is based on the input of phosphate with feed concentrates, dietary phosphate, net import of roughage and the stock of fodder crops for 2005. The output consists of animal products, pet food, net export of compound feed, crop products and manure. An internal cycle redistributes input and output. The sector balance has a surplus of 85 Gg P_2O_5.

Inputs in the soil balance are phosphate from manure, fertilisers, other soil amendments and crop residues. The output is based on P removed with harvested crops (offtake). Although the sector balance and soil balance are calculated differently, both result in a similar estimate of the phosphate surplus (CBS, 2010).

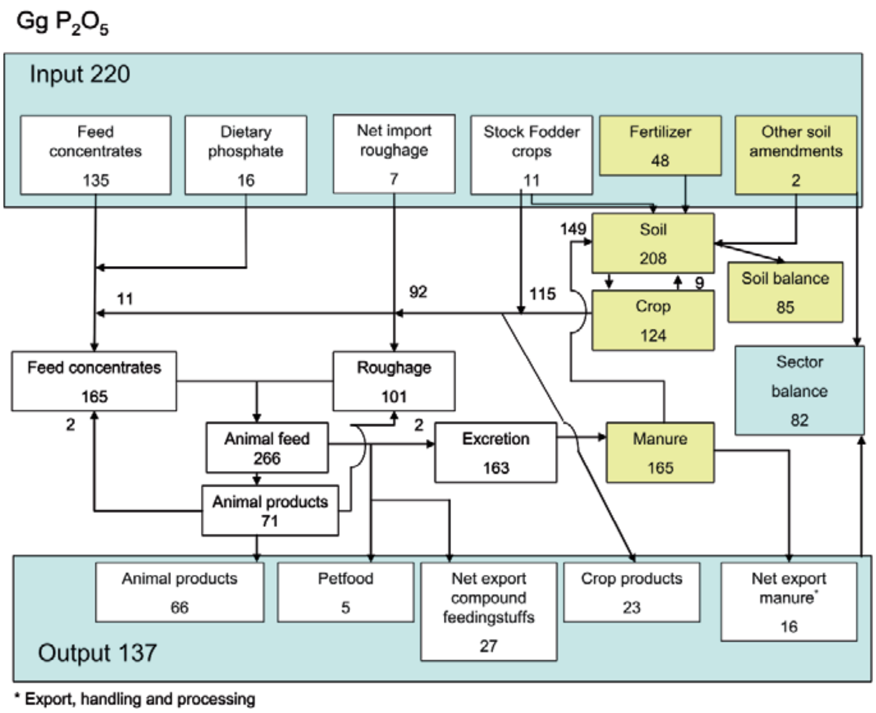


Figure 6.1: Phosphate in Dutch Agriculture in 2005 in Gg P_2O_5 (source CBS StatLine, 2010).

The import of feed concentrates accounts for 61% of the Dutch phosphate input, and mineral fertilisers account for 22%. Dietary phosphates add another 7% to the input. Together they represent 90% of the total phosphate used by Dutch agriculture. The export of animal products accounts for 48% of the output, compound feeding stock accounts for 20%, and crop products for 17%. Manure export accounts for 12% of the output. Together these four outputs represent 96% of the total output. The agricultural phosphate balances show a 37% and 39% surplus for the sector balance and soil balance respectively.

The accumulation of phosphate in soil increases the risk of leaching (section 5.4). It is estimated that 6.9 Gg P_2O_5 leaches annually from Dutch agricultural soils, equal to 9% of all phosphate accumulated in soil (Figure 6.1.). Manure spills to ditches and phosphate losses from horticulture via drainage tubes account for 0.7 Gg (Annex I) and non-agricultural soil contributed 0.9 Gg P_2O_5 into surface waters in 2005. Physico-chemical soil processes and weather events influence these losses and they are therefore not easy to control.

Industry (2.1 Gg) and households (4.3 Gg) emitted a total of 6.4 Gg P_2O_5 to surface waters (Annex I). Although the industry has invested considerably in decreasing the phosphate emission to surface waters, resulting in an emission in 2005 of only 3% compared with 1990 (Compendium voor de leefomgeving, 2010[7]), the prospects for any further decreases are poor. Sewage treatment plants remove 60% of the phosphorus from sewage (Compendium voor de leefomgeving, 2010).

[7] Compendium voor de Leefomgeving, June 2010: http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl, (in Dutch).

6.2 Balancing input and output in the Netherlands

Phosphate is accumulating in the Netherlands, with most phosphate accumulating in soil. Statistical data indicate a surplus (Figure 6.1.). Balancing this surplus requires both lowering input and increasing output. To reduce the Netherlands' soil phosphate surplus of 82 (sector balance) or 85 Gg P_2O_5 (soil balance), reducing the input and simultaneously increasing the output are required. The foreseen shortage of exploitable deposits of rock phosphate makes the recycling of phosphate sources an urgent matter.

On a national scale, inputs via animal feed need to be brought in balance with the output via manure and the by-products of animal production. The current focus in the Netherlands is on how to increase the efficiency[8]of phosphorus use (Schoumans, 2010[9]; Broek et al., 2007[10]). Of prime importance is to align manure production to an agronomic and environmentally acceptable use of phosphorus (TCB, 2008[11]). The balance between input of phosphorus to the soil and the offtake by agricultural products needs to be improved. The following actions are currently being carried out to this end.

1. Reduced phosphate content in feed concentrates

The use of feed concentrates with reduced phosphate concentrations yields animal manure with a lower phosphate content resulting in a lower soil balance input. Manure can be reduced further by increasing the availability of phosphate for the animal. The reduction can be achieved without diminishing livestock numbers or the volume of manure. However, livestock farmers and veterinarians are concerned that reduced-phosphate feedstock may have a negative effect on animal welfare. The standard criteria for phosphate requirements for animals are given by the Centraal Veevoeder Bureau (CVB) of the Animal Feed Product Board (Productschap Veevoeder[12]). Animal phosphate requirements depend on the animal species, physiological status, and the availability of the phosphate forms in the feed.

[8] Phosphorus use efficiency (PUE) is defined as: PUE = tradable outputs / all inputs = (exported crops + exported animals + exported milk, cheese & butter) / (imported animals + imported bedding + imported feed + mineral fertilisers + imported manure + deposition & biological fixation).

[9] Schoumans, O.F., 2010. Mestinnnovaties. http://www.kennisonline.wur.nl/BO/BO-05/006/015/ .

[10] Broek, J.A. van den, G. van Hofwegen, W. Beekman & M. Woittiez, 2007. Options for increasing nutrient use efficiency in Dutch dairy and arable farming towards 2030: an exploration of cost-effective measures at farm and regional levels, Wageningen, Statutory Research Tasks Unit for Nature & the Environment. WOt-rapport 55.

[11] TCB, 2008. Advies Aanwenden van mest A044 (2008). Technische Commissie Bodembescherming.

[12] Productschap Diervoeder: http://www.pdv.nl/index_eng.php?switch=1.

Conditional requirements, such as the duration of the growth phase, also affect phosphate requirements.

These standard criteria are however characterised by the unlimited use of feed concentrates and phosphate. As a result, the coefficients for phosphate use are low and they will probably increase by restricting the use of phosphate (Peet-Schwering et al., 1999). A restricted use of phosphate contents can be obtained by:

- Re-evaluating the phosphorus requirements of the animal. (Valk & Beynen, 2003[13]; Krimpen et al., 2010[14]). The actual phosphorus intake by dairy cattle is, on average, 1.5 times higher than current intake standards recommend, which could lead to a 33 percent intake reduction.
- Increasing the availability of phosphate in feed concentrates. In feed of plant origin, two thirds of total P is present as phytic acid P, which is almost indigestible for pigs (Peet-Schwering et al., 1999[15]). Cattle and poultry are able to partly digest phytic acid P. Microbial phytase has been used since 1991 to increase phosphate digestibility. New strains of phytase-producing micro organisms (Aspergillus ficuum) can increase P digestibility (Krimpen et al., 2010). Plant breeding techniques (including DNA techniques) are used to produce cultivars of maize, wheat, barley, soya and rape with lower phytate contents (Bohlke et al., 2005[16] and Spencer et al., 2000[17]).
- Increasing the use of feed with a lower phosphate content.

2. Reduced import of dietary phosphates[18]

Dietary phosphates are selected for, amongst other reasons, their digestibility which differs between animal species. Dicalciumphosphate has the highest digestibility. Recycling phosphate from animal bones and proteins used to be common practice but was abandoned to prevent the contagion of diseases (Bovine Spongiform Encephalopathy (BSE) or mad cow disease)[19]. This ban was later partially lifted, although feeding animal by-products to the same animal species is still prohibited[20]. Dietary phosphates can be obtained from recycling processes (see 6.3) which creates an opportunity to replace imported dietary phosphate with recycled products.

3. Reduced use of phosphate from mineral fertilisers

Consumption of mineral phosphate fertilisers has declined since 1986 when 82 kg P_2O_5/ha was applied as mineral phosphate fertiliser. This amount was reduced in 2005 to 48 kg P_2O_5/ha[21]. The reduction was obtained by:

- A mineral accounting system, introduced in 1998, which was replaced by phosphate use standards as of 2006. As of 1-1-2010 phosphate use standards are differentiated with respect to the soil P status (LNV, 2008[22]).
- Valorisation of phosphate from animal manures and other organic soil amendments (compost, sludge).
- The more efficient use of mineral fertiliser through placement in the plant row (as opposed to broadcasting), and by actually following the recommendations for phosphate fertiliser based on the actual phosphate status of the soil.

13 Valk, H. & A.C. Beynen, 2003. 47 Proposal for the assessment of dairy cows. Livestock Production Science 79: 267-272.

14 Krimpen, M. van, J. van Middelkoop, L. Sebek, A. Jongbloed & W. de Hoop, 2010. Effect van fosforverlaging in melkveerantsoenen en varkensvoeders op fosfaatexcretie via mest. Rapport 324, Wageningen UR Livestock Science / Animal Science Group Veehouderij B.V., Lelystad.

15 Peet-Schwering, C.M.C. van der, A.W. Jongbloed & A.J.A. Aarnink, 1999. Nitrogen and phosphorus consumption, utilisation and losses in pig production: The Netherlands. Livestock Production Science 58: 213-224.

16 Bohlke, R.A., R.C. Thaler & H.H. Stein, 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate. corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83, 2396–2403.

17 Spencer, J.D., G.L. Allee & T.E. Sauber, 2000. Phosphorus bioavailability of normal and genetically modified low-phytate corn for pigs. J. Anim. Sci. 78, 675-681.

18 dicalciumphosphate (hydrated/ dehydrated, monocalciumphosphate, mono-dicalciumphosphate, magnesiumphosphate, monoammoniumphosphate, calcium-magnesiumphosphate and their sodium forms. Other dietary phosphates are proteins (meat) from animal origin.

19 Regulation (EC) No 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption Official Journal L 273, 10/10/200.

20 Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation) Official Journal L 300/1 14.11.2009.

21 In 2008 the mineral phosphate fertiliser 36.6 kg P_2O_5/ha was used.

22 Ministry of Agriculture, Nature and Food Safety (LNV), 2008. Fourth Action Programme Nitrate Directive (2010-2013).

Phosphate from manure cannot fully replace mineral phosphate fertilisers. Crops with a short growing period and a high daily phosphate requirement will benefit from fertilisation with mineral phosphate fertilisers, particularly at a lower soil P status. Soils with ample or lower ratings benefit from row placement of water soluble mineral phosphate fertilisers. About 43% of the grassland has an ample or lower rating of the phosphate status of the soil, and 24% and 17.7% of the maize land and arable land respectively have an ample or lower rating (Schoumans, 2007[23]).

4. Treatment of manure and other biosolids

Animal manure contains essential plant nutrients. The composition of manure does not always match the needs of specific crops, farm types or regions (Schröder et al., 2009[24]). In general, animal manure cannot substitute mineral fertilisers completely unless it is processed. Phosphate in animal manure is available in the long term, but in the short term availability does not necessarily match crop requirements (i.e. high-phosphate requiring crops such as lettuce or spinach). Manure treatment involves solid-liquid phase separation by sedimentation, centrifugation, drainage or pressurised filtration. The pre-treatment of manure includes the addition of chemicals to promote flocculation and coagulation and the formation of struvites (see section 6.3). Post treatment includes a number of separation techniques e.g. evaporation or membrane filtration of the liquid phase (Hjorth et al. 2010[25]). Techniques using membranes (microfiltration, ultrafiltration, reverse osmosis, nanofiltration) are the most advanced but are still in the research and development phase. These techniques should eventually lead to the development of treatment methods that recover most of the nutrients (phosphate) present in manure and other biosolids, and lead to the production of solid or liquid fractions which can fully replace mineral fertilisers. Strangely enough, struvite is still not permitted as a fertiliser in the Netherlands, although it is widely used in agriculture in Japan, and studies in Sweden have shown that struvite is a better fertiliser than the best available commercial fertilisers. The few plants in the Netherlands that treat animal manure or process water must sell their product as a low-valued secondary phosphate ore to Thermphos.

Manure processing techniques are also used to make products other than mineral fertilisers (Hjorth et al., 2009[26]). Techniques for producing energy from manure and other biosolids include anaerobic digestion to produce methane, incineration, or other techniques such as pyrolysis, torrefaction and gasification to produce other forms of bioenergy. Energy production has substituted odour emission reduction as the main motive for processing manure or other biosolids. Adding olivine powder to digesters eradicates most of the odour problems. Separation of the liquid and solid phase is the most viable technique currently available. Other techniques are still in the research and development stage and the prospects for medium and long-term beneficiation are good.

[23] *Schoumans, O.F., 2007. Trends in de fosfaattoestand van landbouwgronden in Nederland in de periode 1998-2003. Alterra rapport 1537. Alterra Research Instituut voor de groene ruimte, Wageningen. http://library.wur.nl/way/bestanden/clc/1855771.pdf.*

[24] *Schröder. J.J., F. de Buisonjé,, G. Kasper, N. Verdoes & K. Verloop, 2009. Mestscheiding: relaties tussen techniek, kosten, milieu en landbouwkundige waarde. Rapport 287, Plant Research International B.V. Wageningen. http://edepot.wur.nl/50884.*

[25] *Hjorth, M., K.V. Christensen, M.L. Christensen and S.G. Sommer, 2010. Solid–liquid separation of animal slurry in theory and practice. A review. Agron. Sustain. Dev. 30 (2010) 153–180.*

[26] *Hjorth, M., A.M.Nielsen, T. Nyord, M.N. Hansen, P.Nissen, S.G. Sommer, 2009. Nutrient value, odour emission and energy production of manure as influenced by anaerobic digestion and separation. Agron. Sustain. Dev. 29: 329–338.*

Separation yields a liquid fraction with a high inorganic nitrogen and potassium content. The solid fraction has a high organic matter and phosphorus and organic nitrogen content. The solid fraction has proven to have export potential to other regions and countries. The liquid fraction can be used close to the production site i.e. within a radius of 30 km.

5. Phosphate recovery

Phosphate recovery from animal manure and sewage sludge opens up the prospect of removing phosphate from the agricultural sector. Several initiatives to recover phosphate are currently in place. These processes include:

- struvite and dicalciumphosphate production from wastewater treatment plants;
- struvite production from manure and other biosolids, including the liquid and solid phase of manure;
- biochar production by pyrolysis of animal manure and other biosolids;
- phosphate recovery from ash after incinerating manure and composted sewage sludge.

Phosphate recovery leads to national phosphate recycling and presents opportunities to export phosphate abroad. Phosphate recovery is a key topic of current research. A large number of projects are or have been carried out (e.g. RüPhAK, PASCH, MAPAK, EntPAK, DEUS21, BayPAK, SUSAN, REPHOMASTER, PHOSIEDI, PhoBE, REM-NUT etc.[27]).

[27] *For an overview the reader is referred to http://www.phosphorus-recovery.tu-darmstadt.de/.*

6.3 Phosphate sources in the Netherlands

Most of the household and industrial waste in the Netherlands is re-used. In 2005, 60.4 Tg waste was produced of which 83.4% was reused, 11.9% was incinerated, 3.7% was stored in controlled dumps, and 1.1% was discharged to surface water and groundwater (Compendium voor de Leefomgeving, 2010[28]). Waste reuse has been fairly stable since 2000.

[28] *Compendium voor de Leefomgeving, 2010. Afvalproductie en wijze van verwerking, 1985-2007. http://www.compendiumvoorde-leefomgeving.nl/indicatoren/.*

Ash from incineration is a potential source of phosphate. Ash is contaminated with heavy metals and organic contaminants which is currently an obstacle to its complete reuse. Ash is used in the cement industry, road construction, and the brick industry etc. Information on the phosphate content of this ash and its reallocation to different kinds of reuse is incomplete. Data are therefore not yet available.

Sources for phosphorus recycling in the Netherlands are:

- animal manure
- by-products of food production (plant by-products)
- animal by-products

- crop residues
- carbonatation mud from the sugar beet industry (i.e. calcium carbonate residue that remains after raw sugar beet juice has been clarified)
- compost (including black earth)
- sewage sludge

One very important source of phosphorus is human urine. The first pilot projects to separate urine collection and treatment have been started. The first treatment plant for human urine, which recovers the phosphate as struvite, has opened in Zutphen.

Most phosphate that is currently recycled in the Netherlands originates from manure (section 6.2). Next is phosphate from by-products of food production and animal by-products. Other secondary products and waste are re-used, although in relatively small amounts compared with the phosphate from manure, plant and animal by-products.

Phosphate recycled from manure and compost is still mostly used as a nutrient source for crop production, and to a much lesser extent as a secondary phosphate ore by Thermphos. Other uses are currently being investigated. Plant by-products are mainly used as feed, as there is limited use as fuel. Crop residues were traditionally used as soil amendments. Nowadays, biogas production plants are a secondary and growing market for these residues. Carbonatation mud is primarily used as a lime, but it also contains phosphate from the sugar beet and it is therefore also a nutrient source. Other wastes are recycled as raw material for the production of fertiliser or dietary phosphates, or serve as primary products for the chemical industry. The estimated quantities of phosphate from these sources that are re-used in the Netherlands are given in Table 6.1.

Table 6.1:
Re-use of phosphate from different sources in the Netherlands in Gg P2O5.

Source	Estimated quantity
Animal manure	165.0
By-products of food production, plant by-products	113.2
Animal by-products	42.7
Crop residues	9.2
Compost	2.5
Carbonatation mud	1.5
Sewage sludge	0.2

Animal manure

By far the largest amount of phosphate is recycled by using animal manure as a nutrient source. In 2005, 149 Gg P_2O_5 was reused in the Netherlands and 16 Gg P_2O_5 was exported.

By-products of food production, plant by-products

Food production (cereal processors, bakeries, breweries, fruit and vegetable processors, cacao processors, fermentation industries, cheese production etc.) also leads to residues that are all valorised to plant by-products, although the distinction between by-product and waste is not always clearly given (Bouwmeester et al., 2006[29]). Most plant by-products are re-used as feed (intensive livestock and pets). Vis et al., 2003[30], Bouwmeester et al., 2005[31], Bouwmeester et al., 2006, give

[29] *Bouwmeester, H., M.H. Bokma-Bakker, N. Bondt, J. van der Roest, 2006. Alternatieve aanwending van (incidentele) reststromen buiten de diervoedersector. RIKILT Rapport 2006.008.*

[30] *Vis et al., 2003 De diervoederketen en zijn witte vlekken in kaart gebracht. 'door de bomen het bos zien'. Tussenrapport Ketenanalyse Diervoedersector. Deelproject 1 en 2. Den Haag, VWA/RVV, 16-12-2003.*

[31] *Bouwmeester, H., M.H. Bokma-Bakker, N. Bondt & J. van der Roest, 2005. Risicobeheersing bij gebruik van reststoffen in diervoeders, RIKILT, Rapport 2005.001.*

estimates for the quantities of plant by-products and their uses. It is estimated that 113.2 Gg P_2O_5 is re-used[32].

Animal by-products

Of the total production from intensive livestock farms, 32-48% is not suitable for human consumption and it is referred to as animal by-products (RDA, 2006[33]). Around 634 Gg[34] are processed annually into by-products such as blood meal, meat and bone meal (MBM), and feather meal. Animal by-products are used for food, feed, fuel, fertiliser and as secondary products for a large range of industries for the production of (bio)chemicals, pharmaceuticals, porcelain, detergents, photo prints, matches, coatings etc. Approximately 573 Gg is recycled, 55 Gg is incinerated, and 6 Gg is stored in controlled dumps (data 2007). Until the BSE crisis, a major quantity was used as animal feed as a protein source or as dietary phosphate (see 6.2). An estimated 42.7 Gg P_2O_5 is re-used[35].

Crop residues

Crop residues are recycled almost completely in the Netherlands. The majority of 5379 (i.e. 99.1%) of the total estimated quantity of 5428 Gg is returned to agricultural land with an estimated return of 9.2 Gg P_2O_5 (Figure 6.1).

Carbonatation mud

Carbonatation mud from the sugar industry contributed 3.4 Gg P_2O_5.

Compost

Three types of compost are recycled: spent mushroom substrate, compost from vegetables, fruit and garden waste from househol and green compost. Black earth is a mixture of compost and soil.
In 2005, 2.5 Gg P_2O_5 was recycled from spent mushroom compost. 1.4 Gg P_2O_5 of GFT compost was recycled, and 1.1 Gg P_2O_5 of other compost.

Sewage sludge

The amount of phosphate contained in sewage sludge is estimated to be around 27 Gg P_2O_5 (CBS, 2008). Sewage sludge in the Netherlands is mainly incinerated, after which the ash is disposed of or used in the cement industry. Less than 4% (approximately 1 Gg P_2O_5) of the annually produced sewage sludge ash is currently used for phosphate recovery (SNB, 2009). Another 4% is used as a nutrient source (fertiliser).

The major limitation of the use of P from ash in agriculture is the presence of iron ions in the bulk of the sludge, originating from the iron salts that are used to remove phosphorus from waste water. The presence of iron precludes the use of sewage sludge as feedstock for the Thermphos furnace plant in Vlissingen. The use of aluminium instead of iron salts to precipitate phosphate is an alternative, but this technique is more expensive. There are also other methods (see e.g. Duley, 2001) to recover phosphate from sludge and sludge ash, but they have not yet been implemented in the Netherlands.

Potential sources for the recovery of phosphate are human urine, phosphate containing waste water.

[32] *CBS, 2009. Dierlijke mest en mineralen 1990-2008. Centraal Bureau voor de Statistiek, Den Haag; Ehlert, P.A.I., P.H.M. Dekker, J.R. van der Schoot, R. Visschers, J.C. van Middelkoop, M.P. van der Maas, A.A. Pronk, A.M. van Dam, 2009. Fosforgehalten en fosfaatafvoercijfers van landbouwgewassen : eindrapportage Alterra-rapport nr. 1773.; http://www.beuker.nl/index.php; http://www.vandersteltbv.nl/; NEVO-tabel, 2010. http://www.rivm.nl/nevo/ ; Sauvant, D., J.M. Perez & g. Tran, 2002. Tables of composition and nutritional value of feed materials. Table de composition et de valeur nutritive des matières premières destineés aux animaux d'elevage. INRA ISBN-2-7380-1046-6.; Timmerman, M. en M.A.H.H. Smolders, 2004. Mineralenbalans op afdelingsniveau bij vleesvarkens. Praktijkrapport Varkens 35. Scharrer, K. & H. Linser, 1968. Handbuch der Pflanzenernährung und Düngung. Boden und Düngemittel. Springer-Verlag. Wenen – New York.; NEVO-tabel, 2010. http://www.rivm.nl/nevo/ ; Tabellen Mestbeleid 2010-2013 (http://www.hetlnvloket.nl/portal/).*

[33] *RDA, 2006: Raad voor Dieraangelegenheden, 2006. Mogelijkheden tot versoepeling van het verbod op het hergebruik van dierlijke eiwitten. Advies aan de Minister van landbouw, natuur en voedselkwaliteit inzake het in te nemen standpunt ten aanzien van de mogelijkheid tot het versoepelen van het verbod op het hergebruik van dierlijke eiwitten: Haalbaarheid, acceptatie en wenselijkheid. http://www.raadvoordierenaangelegenheden.nl/pages/home.aspx.*

[34] *Compendium voor de leefomgeving http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl.*

[35] *Based on data montage of: Luske, B. & H. Blonk, 2009. Milieueffecten van dierlijke bijproducten. Blonk Milieu Advies B.V. Gouda; Haas, M.J.G. & S.W. Moolenaar, 2004. Inzetbaarheid van SONAC-grondstoffen als meststof. Nutrienten Management Instituut rapport 881.03.; Scharrer, K. & H. Linser, 1968. Handbuch der Pflanzenernährung und Düngung. Boden und Düngemittel. Springer-Verlag. Wenen – New York.; NEVO-tabel, 2010. http://www.rivm.nl/nevo/.*

Human urine

Phosphate recovery from urine requires a modified sanitation system to collect urine and faeces separately. Phosphate from urine can then be precipitated by evaporation or after precipitation into struvite. Various initiatives for separate urine collection have been introduced on a local scale (Smit et al., 2009[36], STOWA, 2009[37]); an overview of the full scale on which this recovery technique is applied in the Netherlands is not available.

A new initiative for the large-scale recovery of phosphate from urine was recently presented by the Rivierenland Water Board and GMB Watertechnologie (STOWA, 2008[38]). They have built a pilot plant to recover phosphate using urine from the Organon 'Women for Women' initiative, as well as from other sources. The pilot plant will have an annual capacity of over 1 million litres of urine, but the amount of phosphate that can be recovered from it as struvite precipitate is unclear.

Waste water

Phosphate is usually recovered from waste water after precipitation into struvite ($MgNH_4PO_4.6H_2O$) or calcium phosphate ($Ca_3(PO_4)_2$) and adding various other chemicals. The struvite process is robust, and only needs limited amounts of MgO.

There is currently only one plant in the Netherlands that produces calcium phosphate pellets from sewage influent (Geestmerambacht sewage works). The phosphate in the pellets is recovered and added to the phosphate rock feed at the Thermphos furnace operation in Vlissingen (Duley, 2001[39]). Phosphate recovery from waste water by struvite precipitation is further only used in some industrial applications, such as a potato processing plant (Lamb/Weston/ Meyer in Kruiningen), a calf manure treatment plant in Putten, and a few bio-mass fermentation installations. No data is available on the amount of phosphate recovered in this way. Klapwijk et al. (2002)[40] estimate that 18 ktons P_2O_5 can be recovered annually by waste water plants.

6.4 Opportunities for a more sustainable use of phosphate

A more sustainable use of phosphate requires the efficient use of the nutrient and re-use of available phosphate sources.
Intensive animal production systems are generally not efficient at phosphate use (Smit et al., 2009). One opportunity to improve the sustainable use of phosphate is to improve nutrient use efficiency in agricultural systems. Re-using phosphate requires adapting the phosphate industry to available secondary sources.

A number of recommendations to achieve this transition are presented in the following sections.

[36] *Smit, A.L., Bindraban, P.S., Schroder, J.J., Conijn, J.G., van der Meer, H.G., 2009. Phosphorus in agriculture: global resources, trends and developments. Report 282. Plant Research International, Wageningen.*

[37] *STOWA, 2009. Nieuwe Sanitatie. URL: http://themas.stowa.nl/Themas/Nieuwe_sanitatie.aspx?mID=7213&rID=846.*

[38] *STOWA, 2008. Projectplan Betuwse Kunstmest versie 210808a, pp. 20. URL: http://themas.stowa.nl/Uploads/nieuwe%20sanitatie/projecten/Betuwse%20kunstmest/projectplan%20Betuwse%20Kunstmest%2021%20augustus%202008.pdf.*

[39] *Duley, B., 2001. Recycling Phosphorus by Recovery From Sewage. Rhodia Consumer Specialties UK Ltd for Centre Europeen d'Etudes des Polyphosphates, pp. 17. URL: http://www.nhm.ac.uk/research-curation/research/projects/phosphate-recovery/index.htm.*

[40] *Schipper, W., A. Klapwijk, B. Potjer, W.H. Rulkens, B.G. Temmink, F.D.G. Kiestra & A.C.M. Lijmbach, 2004. Phosphate Recycling in the Phosphorus Industry. Phosphorus Research Bulletin Vol. 15 (2004) p. 47-51.*

6.4.1 Improving nutrient use efficiency

A key factor is to improve the efficiency of nutrient use. By far the largest amount of our net phosphate is consumed in agriculture (see 6.1). A more efficient use of agricultural phosphate is needed. Options for a better balance of inputs and outputs are given in section 6.2.

The objective of the Fertilisers Act is to introduce equilibrium in phosphate input and output in the agricultural sector by 2015. The amount of phosphate application will depend on the actual soil P status and the focus is to balance the input and output of the soil balance (i.e. the maintenance of fertilisation). This will lead to improved efficiency in nutrient use. In order to avoid using phosphate ores from geological deposits, phosphate should ideally be recycled from a renewable source (e.g. manure, compost, bone meal, biochar, ashes etc.).

Substantial phosphate losses occur during the transportation, processing and preparation of food. It is estimated that 30 to 40% of the food produced in the Netherlands is wasted during production, transportation and storage (LNV, 2009[41]). Moreover, 11-13% of the food purchased by consumers is estimated to be wasted (LNV, 2009).

6.4.2 Improving fertiliser efficiency

1. Regular fertilisers
When fertilising, a substantial amount of P_2O_5 is not available for plants due to instantaneous adsorption and a slower co-precipitation with soil compounds. Placing phosphate in planting rows, in planting holes, or side-application will improve the efficiency of phosphate fertilisers (Smit et al., 2010[42], Ehlert & De Willigen, 2002[43]).

We could learn from the way plants and symbiotic fungi use chelating agents to keep phosphate available. Further research is needed to evaluate the feasibility of this.

2. New fertilisers
Struvite has proven agronomic qualities (Richards & Johnston, 2001[44]). Pure struvite is similar to conventional phosphate fertilisers such as triple superphosphate. But the raw materials used to produce struvite and the production method used will affect the availability of phosphate from struvite. Rapid release characteristics are required if the product is intended for the Dutch market. However, slow release characteristics are favourable for phosphate fixating soils such as oxisols in Brazil or Central Africa, where the slow release of phosphate improves P-availability for plants.

Several measures can be taken to improve the availability of P from struvite. One option is dehydration (and sterilisation) at 110 C, whereby the struvite loses 5 of its 6 bound water molecules, after

[41] *LNV, 2009. Bijlage Nota Duurzaam voedsel. Naar een duurzame consumptie en productie van ons voedsel. Ministerie van Landbouw, Natuur en Voedselkwaliteit, Den Haag, 29 juni 2009.*

[42] *Smit, A.L, A.A. Pronk & P. de Willigen, 2010. Placement of Phosphate Leads to a More Efficient Use of a Finite Resource Proc. 4th IS on Ecol. Fert. Strat. Field Veg. Prod., Ed.: R.U. Larsen, Acta Hort. 852, ISHS 2010.*

[43] *Ehlert, P.A.I., C.A.Ph. van Wijk & P. de Willigen, 2002. Fosfaatbehoefte van vollegronds-groentegewassen, 3. Rijenbemesting. Praktijkonderzoek Plant & Omgeving B.V., Lelystad, PPO-projectrapportnr. 1125232.*

[44] *Richards, I.I. and A E Johnston, 2001. The effectiveness of different precipitated phosphates as sources of phosphorus for plants. Report on work undertaken for CEEP1, EFMA (European Fertiliser Manufacturers Association), Anglian Water UK, Thames Water UK and Berlin Wasser Betriebe.*

which it dissolves more easily. Another option is to produce K-struvite instead of the more common NH_4-struvite, e.g. by an ammonia-stripping process followed by K-struvite precipitation, which is a technique that is already available. The agricultural value of K-struvite should be further investigated because its direct application as a fertiliser seems more logical than its current use as a secondary phosphate ore.

6.4.3. Alternative sources of phosphate

1. Enhanced release of the accumulated phosphate fraction from soils

Over time, agricultural topsoils have accumulated a large amount of phosphate. As estimated in Chapter 5, phosphate accumulated in agricultural topsoils represents at least 40-90 years of phosphate fertiliser application. It seems logical to see if, and how, this phosphate 'resource' can be exploited in the future.

Average phosphate offtake is currently 95 kg P_2O_5/ha on mowed grassland and 50 kg P_2O_5/ha on arable land (Ehlert et al., 2009[45]). Accumulated residual phosphates from fertiliser and manure are available to crops (Ehlert et al., 2006[46]). How these soil phosphate pools can be used as an available buffer at reduced phosphate use is uncertain. Micorrhizae might possibly be helpful, but its significance to disclose soil phosphate fraction through its extensive network of hyphae and its biochemical alteration of the rhizosphere is still unclear.

[45] *Ehlert, P.A.I., P.H.M. Dekker, J.R. van der Schoot, R. Visschers, J.C. van Middelkoop, M.P. van der Maas, A.A. Pronk, A.M. van Dam, 2009. Fosforgehalten en fosfaatafvoercijfers van landbouwgewassen : eindrapportage Alterra-rapport nr. 1773.*

[46] *Ehlert, P.A.I., Salm, C. van der, & Schoumans, O.F., 2006. Long-term effect of soil of restricted use of phosphate fertilisers. The International Fertiliser Society. Proceedings No: 593.*

2. Use of phosphate from natural areas

In former eras, litter and sods from forests and heathland were applied to fertilise the land. Analogous to this approach, nutrient-rich topsoil that has been removed to speed up nature restoration, could be used to improve the fertility of agricultural land. In principle, any organic waste from nature restoration projects could be applied (e.g. litter, woodchips etc.). This is currently hampered by existing regulations for soil transportation and/or requirements for the application of organic material on agricultural land.

3. Use of aquatic plants as animal feed or as biomass for energy production

Eutrophication in temperate climates is usually accompanied by the growth of Lemna species (duckweed) and other plants. Lemna accumulates dissolved phosphate from surface water and the phosphate returns to the water once the plants decay. Harvesting Lemna will therefore decrease eutrophication. After harvesting, these fast-growing plants can be used as relatively cheap animal feed. Aquatic plants can also be used to produce bio-energy, and phosphate from the plants can be recovered as struvite after fermentation (Schuiling, 2006[47]). The economics, including factors such as preventing eutrophication, the price of biogas, and phosphate recovery need to be worked out. The far greater ecological problem of the water hyacinth in tropical countries (Eichhornia crassipes) could be tackled

[47] *Schuiling, R.D. 2006. Co-vergisting van varkensmest met andere residuen. Spil 223 – 224, nummer 2, pp 17-19.*

along the same lines, making it possible to recover large volumes of phosphate, as well as significant volumes of biogas. It is recommended that biofuel production from land-based crops be replaced as far as possible by biofuel production in algal farms along coastlines, not only because on land it competes with food production and scarce irrigation water, but also because algae make more efficient use of the available phosphate.

4. Recovery of phosphate from bio-energy waste streams
An increasing amount of energy is being derived from biomass, either by biomass fermentation or by biofuel production. Bio-energy production does result in waste (i.e. ash, chars or residues after fermentation). Phosphate is accumulated in this waste which is a potential source for phosphate recovery. Several routes for phosphate recovery are currently being investigated (Schoumans, 2010).

Traditional waste burning methods will be replaced in the near future by other more energy yielding methods (gasification, pyrolysis, torrefaction). Although the focus is on improving the performance of the energy production, new lines on phosphate recovery are being entered. One of these lines is the char (biochar) that remains after manure pyrolysis. This char can be reused as a soil phosphate-containing amendment. As a soil amendment, biochar improves the soil condition, and returns the phosphate extracted for biomass production thereby closing the agricultural P-cycle. Biochar acts as a sink for atmospheric carbon dioxide as the carbon is fixed strongly into the biochar and thereby delays oxidation and subsequent CO_2 production.
Last, but certainly not least, ash from burning waste does contain a considerable amount of phosphate and it is a potential source of phosphate. Selected ash is used as a phosphate source. One of these sources is ash from burning sewage sludge. Currently about 30-50% is recycled but there are prospects to increase this to 90% re-use (W. Schipper in Smit et al., 2009).

6.5 Recommendations

Increased consumption and the resultant future scarcity of phosphate resources are good reasons to move on to a more sustainable use of phosphate:

- Geological/Geo-political: the Netherlands is fully dependent on the import of phosphate from abroad, and the worldwide resources of phosphate are limited.
- Economic: future phosphate prices are likely to remain high at 50 – 100 US$/ton, which increases the cost of fertiliser and subsequently of animal feed prices.
- Economic/Environmental: elevated phosphate prices have increased the economic feasibility of different forms of phosphate recycling.
- Environmental: the need to balance input and output (soil balance) to reduce nutrient losses to surface water and groundwater in order to meet EU water quality targets.

Various options for reducing losses and further recycling have been reviewed in the previous sections. The effective options for the short term are:

1. The most significant reduction in phosphate consumption and subsequent reduction of losses can and will be achieved in the Dutch agricultural sector, which is responsible for the bulk of the net Dutch phosphate consumption and around 40% of the total phosphate losses. Improving the efficiency of nutrient use is essential. Reducing the agricultural consumption of phosphate is already enforced through the Fertilisers Act 2006, which has had a major effect. Compared with 2005, the newly implemented phosphate standards will lead to a reduction in phosphate use from manures and fertilisers of 30-40% (i.e. 71-95 Gg P_2O_5). This reduction will depend on the decrease of the phosphate status of the soil caused by the reduction of phosphate use. Soils differ in their phosphate buffering capacity. It is, at present, not possible to give an estimate of the effect of the buffering capacity of Dutch soil on the reduction of phosphate from fertilisers and manure.
2. In addition, reducing the phosphate content of animal feed and improving its availability (e.g. using biorefinery), the production of fertiliser from manure and an increased export of manure will contribute to a more sustainable and balanced use of phosphate and to an increase in phosphate use efficiency. A rough estimate is 20 – 30 Gg P_2O_5.
3. Thirdly, a reduction in phosphate loss can be achieved by using an alternative approach to phosphate removal from urban and industrial waste water, e.g. by using aluminium salts. Phosphate precipitated in the sewage sludge can then be used as raw phosphate ore for the production of fertiliser. It is estimated that 18 Gg P_2O_5 can be recycled in this way.
4. Another measure to further reduce agricultural consumption is the in-row placement of phosphate fertilisers. It is estimated that 10 Gg P_2O_5 of fertiliser phosphorus can be used more efficiently.

The various measures to reduce losses and for phosphate recycling would result in a total annual saving of between 119 and 153 Gg P_2O_5. This shows that a substantial reduction can be achieved without rigorous changes in policy and legislation and the reuse of available phosphate in the Netherlands.

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Annex I: Phosphate balance for the Netherlands (2005)

Item					Ton P2O5
Total balance of minerals (1)	Supply	Total			1083.8
		Import	Animal feed		142.1
			Food products		169.6
			(In)organic compounds		749.3
		Transboundary rivers			22.9
	Discharge	Total			900.5
		Export	Animal feed and manure		43.5
			Food products and organic waste		185.6
			(In)organic compounds		648.5
		Discharge major rivers and North Sea			22.9
	Accumulation	Total			183.3
		Agricultural soils and groundwater			77.9
		Non-agricultural soils and groundwater			39.0
		Fresh surface water			9.2
		Other items			57.3
Mineral balance soil and groundwater (2)	Supply	Total			247.5
		Agricultural soils	Total		208.5
			Animal manure		1.489
			Inorganic fertilisers		48.1
			Other organic fertilisers		9.2
			Deposition		0
			Other input		2.3
		Non-agricultural soils	Total		39.0
			Local input	Sewage sludge	0
				Dredged mud	4.6
				Other waste	11.5
			Diffuse input	Deposition	0
				Other diffuse input	22.9
	Discharge	Total			130.6
		Agricultural soils	Total		130.6
			Losses with crops		123.7
			Surface run-off		6.9
		Non-agricultural soils run-off			0
	Accumulation	Total			116.9
		Agricultural soils and groundwater			77.9
		Non-agricultural soils			39.0

Mineral balance fresh surface water (3)	Supply	Total		36.7
		Major rivers (Rhine, Scheldt, Meuse)		22.9
		Discharge	Industry	2.3
			Households	4.6
			Agriculture	0.0
		Agricultural soils		6.9
		Non-agricultural soils		0
		Deposition		0
	Discharge	Total		27.5
		North Sea		22.9
		Dredged mud		4.6
	Accumulation			9.2

Source: CBS, Fosfor in The Nederlands, 2005 (http://statline.cbs.nl, accessed on 05 August 2009).

Samenvatting

De fosfaatbalans – Huidige ontwikkelingen en toekomstvisie
Schuiling, R. e.a.
InnovatieNetwerkrapport nr. 10.2.232E, Utrecht, februari 2011.

Fosfaat is onmisbaar voor de landbouw en speelt daarom een essentiële rol bij de wereldwijde productie van voedingsmiddelen en biobrandstoffen. De landbouw kent geen alternatief voor fosfaat en daar komt nog bij dat een aanzienlijk deel van onze jaarlijkse fosfaatconsumptie in het milieu belandt, waar het nauwelijks meer van nut is voor de landbouw. Fosfaat is een onvervangbare, en eindige, natuurlijke hulpbron die steeds sneller wordt verbruikt.

De geleidelijke uitputting van de hoeveelheid beschikbaar fosfaat in combinatie met de recent gestegen fosfaatprijzen betekent dat wij onze fosfaatconsumptie zullen moeten aanpassen. Naast economische en geopolitieke redenen is dit ook noodzakelijk vanwege de vermindering van de uitstoot van fosfaat naar het milieu.

Er zijn twee manieren om de verminderde beschikbaarheid van fosfaat het hoofd te bieden:
- de reservebasis vergroten;
- een groter percentage recyclen.

Ook als we de reservebasis vergroten – waartoe volop gelegenheid is – is het onvermijdelijk dat de fosfaatindustrie vroeger of later zal moeten veranderen van een op mijnbouw gebaseerde bedrijfstak in een recyclende bedrijfstak.

Hoofdstuk 2: Wereldwijde fosfaatproductie, -reserves en -exploitatie
Fosfaat wordt hoofdzakelijk gewonnen uit fosfaathoudend gesteente

(20-35% P_2O_5). Belangrijke producenten van fosfaatrots zijn Marokko (inclusief de Westelijke Sahara), China en de VS, die samen goed zijn voor 65% van de wereldproductie. Europa produceert op dit moment geen onbewerkt fosfaaterts en importeert al het ruwe fosfaat en fosfaatkunstmest uit het buitenland.

De gemeten en geïndiceerde economische fosfaatvoorraden zijn naar schatting goed voor 15.000 miljoen ton fosfaatrots, terwijl de reservebasis, inclusief marginale en sub-economische fosfaatertslagen, wordt geschat op 47.000 miljoen ton fosfaatrots. Dat komt overeen met respectievelijk 5000 miljoen en 16.000 miljoen ton P_2O_5.

De productie van fosfaatrots door mijnbouw is het laatste decennium licht toegenomen en de jaarlijkse productie bedraagt momenteel ongeveer 167 miljoen ton. Als gevolg van de stijgende fosfaatprijzen heeft de exploitatie van deze natuurlijke hulpbron een nieuwe impuls gekregen en momenteel worden in bijvoorbeeld Mali en Namibië de mogelijkheden van onlangs ontdekte fosfaatreserves geëvalueerd. Door de oplopende fosfaatprijzen zullen de omvang van de voorraden en reserves in de toekomst toenemen. Bij prijzen rond $50-100 per ton zal onze huidige reservebasis naar schatting ongeveer verdubbelen naar 100.000 miljoen ton fosfaatrots.

Hoofdstuk 3: Gebruik en consumptie van fosfaat op wereldwijde schaal

Fosfaatsteen wordt hoofdzakelijk gebruikt voor de productie van minerale kunstmest, zoals diammoniumfosfaat (DAP) en tripel superfosfaat (TSF), gemiddeld goed voor 74% van de wereldwijde consumptie van anorganisch fosfaat. Voor dit wereldwijde gemiddelde is de rol van organisch fosfaat, in de vorm van diervoeder en voedingsmiddelen, buiten beschouwing gelaten. In sommige landen, waaronder Nederland, is de consumptie van organisch fosfaat veel belangrijker dan de consumptie van anorganische kunstmest.

De vier grootste (netto) verbruikers van fosfaatkunstmest zijn China, de VS, India en Brazilië, allemaal grote landen met een omvangrijke landbouwsector. De wereldwijde consumptie per hoofd van de bevolking vertoont grote verschillen tussen het Westen (> 20 kg P_2O_5 per hoofd, bijvoorbeeld in de VS, Australië, Canada en Nieuw-Zeeland) en de ontwikkelingslanden, bijvoorbeeld grote delen van Afrika (< 1 kg P_2O_5 per hoofd). Europa zit daar wat betreft de consumptie van anorganische fosfaatkunstmest tussenin.

De consumptie van fosfaatrots is de afgelopen 100 jaar gemiddeld met ongeveer 3,4% gestegen, hoewel de fosfaatprijzen redelijk stabiel zijn gebleven (in 1998 fluctueerden de prijzen tussen $26 en $43 per ton). Pas in de afgelopen twee jaar zijn de fosfaatprijzen snel gestegen, van ongeveer $30 per ton in 2005 naar $113 per ton in 2008. Daarnaast maakte de Amerikaanse 'Geological Survey' in 2008 melding van bijzonder hoge spotprijzen van $500 per ton inclusief kosten, verzekering en vervoer (CIF). Hoewel deze hoge prijzen in de nabije toekomst ongetwijfeld zullen dalen, behoren lage fosfaatprijzen voorgoed tot het verleden.

Hoofdstuk 4: Toekomstige trends in het fosfaatgebruik en de toereikendheid van natuurlijke hulpbronnen
Aan de hand van een aantal scenario's voor de wereldwijde fosfaatconsumptie wordt geschat in hoeverre de huidige fosfaatvoorraden (zowel geïndiceerde als daadwerkelijk gemeten economische reserves) en reserves (inclusief marginale en subeconomische reserves) toereikend zijn, daarbij rekening houdend met de gevolgen van toenemende biobrandstofproductie. Hoewel met name de rol van biobrandstof hierbij lastig te beoordelen valt, is het waarschijnlijk dat de huidige voorraden ergens tussen 2040 en 2070 uitgeput zullen raken, en de reserves tussen 2100 en 2150.

Deze schattingen komen overeen met eerdere prognoses, maar voor de omvang van de voorraden en reserves is uitgegaan van een fosfaatrotsprijs van $20-40 per ton. Bij prijzen van $50-100 per ton zullen de toekomstige reserves ongeveer verdubbelen en nog wel enkele eeuwen toereikend zijn.

Hoofdstuk 5: Fosfaat in Nederland
Het netto fosfaatgebruik in Nederland bedraagt momenteel ongeveer 183.000 ton P_2O_5 (ongeveer 11 kg P_2O_5 per hoofd van de bevolking), waarvan het grootste deel in organische vorm (diervoeder: 59%). Het aandeel van anorganisch fosfaat, zoals in kunstmest en diervoedertoevoegingen, is een stuk kleiner (35%). Daaruit blijkt dat de consumptie van anorganisch fosfaat in de vorm van minerale kunstmest niet altijd een goed beeld geeft van het totale fosfaatgebruik, met name bij landen die voor een groot deel afhankelijk zijn van de invoer van veevoer, zoals Nederland, België en Denemarken.

Sinds begin jaren tachtig is het totale fosfaatgebruik in Nederland met ongeveer 47% gedaald. Deze daling is het gevolg van lagere fosfaatgehalten in diervoeders (dankzij toevoeging van fytase) en minder gebruik van anorganische fosfaatkunstmest en andere vormen van fosfaat (bijvoorbeeld in wasmiddelen). Recente nieuwe Nederlandse wetgeving inzake het gebruik van kunstmest op landbouwgrond, waardoor tussen nu en 2015 de maximaal toegestane hoeveelheden kunstmest geleidelijk worden verlaagd, zal naar verwachting leiden tot een verdere daling van het fosfaatgebruik in de landbouw.

Als gevolg van een overmatig gebruik van minerale kunstmest en organische mest zijn er aanzienlijke hoeveelheden fosfaat in Nederlandse landbouwgrond beland. De P_2O_5-concentraties zijn gemiddeld verdrievoudigd en een aanzienlijk deel van de grond is verzadigd met fosfaat. Naar schatting bedraagt de hoeveelheid fosfaat in landbouwgrond momenteel ongeveer 1,9 miljoen ton P_2O_5 als gevolg van zo'n 40 jaar kunstmestgebruik. Een deel hiervan zal geleidelijk beschikbaar komen voor gewassen, wat mogelijkheden biedt voor het terugdringen van het fosfaatgebruik zonder oogstdaling van betekenis.

Hoofdstuk 6: Fosfaatrecycling en aanbevelingen voor duurzaam gebruik
Het toenemende fosfaatgebruik en de daaruit voortvloeiende schaarste van fosfaat als natuurlijke hulpbron in de toekomst zijn voldoende

reden om over te stappen op duurzamer fosfaatgebruik:

- Geologisch/geopolitiek: Nederland is volledig afhankelijk van de invoer van fosfaat uit het buitenland en het wereldwijde aanbod aan fosfaat is beperkt.
- Economisch: in de toekomst zullen de fosfaatprijzen naar verwachting hoog blijven, rond $50-100 per ton, waardoor kunstmest duurder zal worden en als gevolg daarvan ook de prijzen van diervoeders zullen stijgen.
- Economisch/milieutechnisch: de hogere fosfaatprijzen vergroten de economische haalbaarheid van diverse vormen van fosfaatrecycling.
- Milieutechnisch: het is essentieel om een balans te vinden tussen input en output om verlies van meststoffen in het oppervlakte- en grondwater tegen te gaan en te kunnen voldoen aan de Europese doelstellingen voor waterkwaliteit.

In de verschillende hoofdstukken zijn verschillende opties aan bod gekomen voor het verkleinen van de verliezen en bevorderen van recycling. Effectieve opties voor de korte termijn zijn:

1. De grootste vermindering van het fosfaatgebruik (en de daaruit voortvloeiende vermindering van verliezen) kan in Nederland worden gerealiseerd in de landbouwsector, die verantwoordelijk is voor het overgrote deel van de Nederlandse fosfaatconsumptie en ongeveer 40% van het in totaal verloren gegane fosfaat. Er wordt al een vermindering van het fosfaatgebruik in de landbouw afgedwongen door de Meststoffenwet van 2006. Deze heeft verstrekkende gevolgen: in vergelijking met 2005 zullen de nieuwe normen voor fosfaatgebruik leiden tot een daling van fosfaat in de vorm van meststoffen en kunstmest met 30-40% (71-95 Gg P_2O_5 per jaar).
2. Vermindering van de hoeveelheid fosfaat in diervoeder en een betere beschikbaarheid daarvan (bijvoorbeeld door middel van bioraffinage), de productie van organische meststoffen uit dierlijke mest en steeds meer export van mest zullen leiden tot een vermindering van de fosfaatinput van 20-30 Gg P_2O_5 op jaarbasis.
3. Fosfaatverlies kan worden tegengegaan door over te stappen op een andere methode voor de verwijdering van fosfaat uit stedelijk en industrieel afvalwater, bijvoorbeeld met behulp van aluminiumzouten. Fosfaat uit rioolslib kan dan worden gebruikt als ruw fosfaaterts voor de productie van kunstmest. Op die manier kan er 18 Gg P_2O_5 per jaar worden gerecycled.
4. Het in de voren inbrengen van fosfaatkunstmest kan naar schatting de fosfaatinput verlagen met 10 Gg P_2O_5 per jaar.

De diverse maatregelen om de input te verlagen en verliezen tegen te gaan leveren een besparing op jaarbasis op van 119-153 Gg P_2O_5. Daarmee is duidelijk dat een combinatie van verschillende maatregelen de fosfaatbalans in Nederland aanzienlijk kan verbeteren, zodat kan worden voldaan aan nieuwe uitdagingen op het gebied van geopolitiek, economie en milieu.