Nuffield Farming Scholarships Trust

The Frank Arden Award 2011

"Fertilisers for the Future"

A Phosphorus Perspective

Nik Johnson

April 2012

A note regarding the Arden Scholarship Award

The Arden Award is different from the UK generic "Nuffield" Awards.

In 1998 the family of the late Frank Arden endowed the Nuffield Farming Scholarships Trust with a fund to offer a biennial award to study topics of significant importance to British agriculture. Unlike generic Nuffield awards, the study topics are specified by the Trust, and the studies themselves are meant to be more in-depth and scientific in nature than the standard "Nuffield". There are no age limits for "Arden" applicants.

Previous studies have considered the image of British agriculture, the impact of the accession countries on European agriculture, the carbon footprint of British agriculture and the application of new technologies to transform UK agriculture and agri-food industries.

For the 2011/12 Frank Arden study, the specified study topic 'Life after manufactured fertilisers' invited candidates to consider how plant nutrients can be more efficiently used and to identify new and novel sources of these nutrients. The Selection Committee made the Award jointly to Nik Johnson and Mark Tucker.

This is Nik Johnson's report and researches the technical position vis a vis Phosphorus. It was not his intention to visit other farmers but to investigate the highest levels of scientific research.

Mark Tucker concentrated his study on Nitrogen and has written a separate report.

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Contents

End of SECTION A

1. Executive Summary

1(a) Introduction

The structure of both the main report and this executive summary has been put into two main sections. The first (Section A) looks at the science behind Phosphorus Use Efficiency (PUE) by plants; and the second section (B) looks at the wider supply and recycling aspects of the mineral. This in essence has given me the opportunity to examine the detailed science of PUE alongside the broad aspects of the commodity's production, and the political and environmental influences on its supply now and in the future.

Phosphorus is an essential element in every living cell of all life forms on the planet. The nutrient is unsubstitutable and irreplaceable, and unlike many other essential nutrients, the global Phosphorus resource is limited. The present processes of using Phosphorus for crop fertilisation are depleting this reserve, and although the time scale for this depletion is of some wider debate, the high grade, easily assessable sources are rapidly being used. We will, I believe, over the next decades be looking at increased costs for the nutrient caused by increased mining and processing costs regardless of whether total reserve figures may increase.

The uses of mined Phosphorus fertilisers have over the past century helped facilitate the 'green revolution'. This has fed a world population which has expanded from approximately 1.6 billion in 1900 to 7 Billion in 2012, an increase of over 400%. Meanwhile the farmed area across the world has only doubled. The population of the world continues to increase and so will the world's requirement for food. This is exacerbated by our use of crops for non-food uses on a scale that the 20th Century did not experience.

Agriculture's reliance on manufactured fertilisers of all types has created a dependence upon them. With reference to Phosphorus, this has resulted across many developed world farming systems in an over-application of the nutrient. This trend is being reversed in certain cases, and the UK has, for over 10 years, been failing to replace the Phosphorus removed by crops (*British Survey of Fertiliser use 2010).* Over-application however is still happening, especially identified in those specific areas where animal wastes containing high levels of Phosphorus nutrition have been applied repeatedly to land, which during cropping does not utilise that nutrition in the same proportion. This then creates the circumstances where Phosphorus can build and become a pollutant in water systems with the resultant costs associated with clean up, and subsequent legislation and controls. This environmental impact must not be underestimated. The structures of entire farming systems may need to change as a result of legislation regarding the use of Phosphorus, or the production and costs associated with disposing of animal wastes. For example, the transfer of livestock production systems to the middle of arable cropping regions where the feed for these livestock businesses is produced.

1(b) Summary of Section A: Phosphorus Use Efficiency (PUE)

In a UK context, I have aimed to highlight my considered view on aspects of PUE that are useful to a UK farmer. The following is a summary of my conclusions:-

- Farming practitioners need to recognise the importance of the careful management of all Phosphorus 'Pools', as described in the detailed report. This understanding of how Phosphorus exists in the soil will lead to farming practices which complement PUE rather than hinder it.
- In understanding the sources of Phosphorus already in the soil, the soil environment is just as important as the form of Phosphorus applied. This will therefore encourage the use of different sources of Phosphorus in agriculture.
- A healthy, well-structured soil with a wide range of Phosphorus sources is more able to supply plants with the Phosphorus that they require in normal arable cropping systems.
- Farmers need to structure the management of Phosphorus over a longer time scale, and not to think about Phosphorus in a yearly context as with Nitrogen, but over a 'rotational' period. Also farmers must recognise that this rotational period may be up to and over 10 years depending on particular cropping systems.
- Practitioners must recognise the complexity of Phosphorus in the soil environment and appreciate the wide range of factors which have an effect upon a plant's ability to acquire Phosphate.
- Sustainable Phosphorus use should target a Phosphorus balance where Phosphorus inputs are equal to Phosphorus outputs, while seeking to minimise Phosphorus inputs.
- There is a need for wider recognition across all stakeholders (public, industry, governments) of the value of wastes as a viable and strategically important supply of Phosphorus and other nutrients.
- RB 209 needs to develop to provide the management tools for farmers to increase PUE and to guard against unnecessary/unscientific regulation, while remaining simple and effective to use, as it is now.
- Where UK farming systems have today 'good' indices for Phosphorus, i.e. between 1 and 3, the amount of Phosphate supplied should aim to replace that removed by production over the cropping cycle to maintain or increase these indices.

- Phosphorus Use Efficiency (PUE) for a UK farmer can be best achieved by maintaining the soil solution above the critical level for the soil and cropping type and encouraging increased total rooting area.
- Different soils can sorb Phosphorus in differing amounts. This reduces the ability of plants to access the Phosphorus in the soil. A better understanding of the systems used by plants to access their Phosphorus requirement is needed. This understanding should lead to a better use of all the residual sources of soil Phosphorus, such that a sustainable point of PUE can be attained across all cropping systems.

UK farming needs to develop systems that assist in unlocking the residual Phosphorus already bound to soils. This will probably come largely from plant breeding of cultivars that have better scavenging systems for Phosphorus without sacrificing yield potential, but it may also come from better understanding the relationships between micro-biota and plants. These systems, however, are not the long term solution and the best we can hope for in sustainable Phosphorus fertilisation at present is the perfect Phosphorus balance where our inputs match our outputs. It is, I believe, achievable across many UK cropping systems, and could buy valuable time to develop the longer term solutions in Phosphorus security.

1(c) Summary of Section B: Phosphorus Supply

The following points are listed within a UK context:-

- Regardless of the upwardly revised figures for total Phosphorus reserves across the world (*USGA. 2011*) the long term importance of Phosphorus as a strategic commodity needs to be understood at all levels from farm through consumers to government.
- The longer term solutions to Phosphorus security lie in managing the complete Phosphorus life cycle. This needs to be done firstly by recognising the scales at which Phosphorus is transported around the globe in produce and waste, and then identifying the points at which efficient recovery and recycling of Phosphorus can be achieved.
- UK farming does need to address the impact of Phosphorus as an environmental pollutant, and to extend the management principles that have worked successfully in other areas, but duly adapted to Phosphorus, without detriment to yield potential. This, I believe, is achievable and the factors are not mutually exclusive.
- A wider recognition across all stakeholders (public, industry, governments) of the value of wastes as a viable and strategically important supply of all nutrients,

especially Phosphorus. This is a reiteration of a bullet point from the section A summary, but is relevant here against securing Phosphorus supply.

- We need to better understand and recognise the movement of Phosphorus through nutrient cycles, which presently sees Phosphorus being mined, passing through the food productions system into the human food chain, and then into waste waters and the seas.
- To develop 'closed loop systems' at whatever scale is appropriate from farm to continental scales, to recycle the Phosphorus back to the beginning of the food production system.
- To develop feeds that release their Phosphorus to the animals more efficiently or add phytases to feed to increase Phosphorus absorption by animals with the resultant reduction of Phosphorus in manure and reduce the need for Phosphorus supplements.

The future of Phosphorus security in the UK over the longer period may mirror some of those issues that will also affect the use of energy and its security. The geopolitical aspects of Phosphorus use, and the threat of the extraordinary event - extreme weather for example - may come to restrict Phosphorus supplies at an unexpected time. The pressure from legislation with reference to water quality specifically will be the driving force for Phosphorus use and/or recovery over the next 10 to 20 years. I believe that, as the costs of producing Phosphorus fertilisers increase over the same period, the viability of recycling systems at certain scales will increase the percentage of Phosphorus recycled. This will still not be enough to maintain the longer term requirement for Phosphorus by UK farming, but it should begin the trend by agriculture to source the required nutrients from other production streams not previously considered.

2. Foreword

I am a 35 year old Lincolnshire arable farmer with more than a passing interest in fertiliser use, as I derive my main income from advising, marketing and applying a various range of base P&K fertiliser products into the arable sector of the UK. In the course of my work I deal with a wide range of farming businesses and personnel, and I have been continually bombarded with conflicting arguments around the science of Phosphorous fertilisation. Farmers, agronomists, industry and science have to date been vociferous in their interpretation and application of Phosphorus fertilisation strategies. With this wide spectrum of views, which I have been subjected to as both a farmer and a FACTS-qualified fertiliser advisor, I felt a need to take stock of the science to date.

The past seven months have been challenging from many angles as I have had to step out of my sphere of influence and activity both in my home life and in my business. This has been difficult personally, and could not have been possible without the efforts of all my family and work colleagues who have given me their time and made sacrifices for the benefit of this opportunity. I thank them all greatly.

The reasons for my enthusiasm in completing this report are due to a number of factors. I believe that it is important for the reader to understand some of my motivations, and hence my drive to find the answers to particular questions. I have at all times tried to remain open minded towards those persons with whom I have spent time, from whatever field of expertise, and to formulate my thoughts only after a period of reflection. I specifically would like to thank a Nuffield scholar from Canada, John Lohr, for making me re-assess my default position at every turn.

I began with a number of basic questions; however these developed and broadened in scope and complexity throughout my study:-

- How exactly does Phosphorus get taken up by the plant?
- What processes in the soil affect uptake?
- How do we as farmers affect Phosphorus Use Efficiency?
- What is the best way to use Phosphorus in UK farming systems?
- What are the long term concerns for Phosphorus Supply in the UK/World?
- How do we better interpret soil Phosphorus tests for Phosphorus use management?

My aims were:

- To visit and talk with those scientists who are leading the way in Phosphorus science across the world.

- To understand the latest research and appreciate the work that is still to be done in the future in understanding Phosphorus in agriculture.
- To look also at the wider aspects of Phosphorus supply on a world scale, and the possible effects that changes in the dynamics of supply may have on farming practices in the UK.

This report does not aim to offer specific advice on agronomic practice, but to challenge the accepted thinking of Phosphorus fertilisation. By trying to understand the complexities of Phosphorus in soils we may better be enabled to adapt our management principles to enhance the efficient use of this nutrient.

Frank Arden, in whose name the research project has been conducted, was a technical innovator amongst British arable farmers, and this ethos has always been at the forefront of my mind during my research. This report brings together my discussions with academics, agronomists, researchers and the results found in many scientific papers from a range of experts around the world, and attempts to focus the detail through the lens of a UK farmer. Because of the complexity of Phosphorus and the technical rather than practical focus of my research, some of the detail in this study may make for a very technically and less practical/case study-based written report, and for this I apologise. Time constraints limited this aspect, but I have endeavoured to maintain as clear a language as possible. I have spent time with the leading scientists and researchers around the world after I made the conscious decision to steer away from practising farmers in most cases. This was because I wanted to get a completely different perspective, and not be clouded with the dark arts of practical farming in the 21st Century.

This approach has led me to the first conclusion that the link between research and practice is somewhat disjointed in the UK as well as in other countries. It appeared in my later meetings, when my knowledge of the science was greater, that the scientists were gleaning as much from me and my practical experience, as I was from them with their specific focused area of research knowledge. I was unsurprised at the lack of agriculture's awareness of the latest science (surely that's the purpose of the Arden Project?) but I was perplexed by the lack of awareness of the science community of the development of UK agriculture and its ability to discover and try new systems of farming.

I should like to thank personally Steve and Meryl Ward, who together constructed the Arden Award, and with whom I met before embarking on my travels. I should also like to thank the Crown Estate and the Frank Parkinson Agricultural Trust who jointly funded this study. Without their support I would not have had this opportunity to expand my experience and knowledge. And I wish to thank John Stones, ever enthusiastic with advice, voice and hands, plus the Nuffield Arden Selection Committee who hopefully saw a potential in my ability to tackle this particular subject.

3. Introduction

Phosphorus is essential to sustain all life. As with many other commodities in the 21st Century, the human race has become extremely good at finding, developing, transporting, using and consuming Phosphorus as a commodity. That does not automatically mean that we use it in an efficient manner or a sustainable way, or even that we know or understand these systems. In the farming industry, where we take one set of commodities to generate production of another set of commodities across the globe, vast quantities of resources are used on a scale to which many other industries do not get close. Farming has such a wide impact on the face of the earth in terms of land management, water quality and food security, that efficiencies of a 'small' input such as Phosphorus are often not considered by the farmer, let alone the consumer. So when we consider the fact that a commodity such as Phosphorus may 'run out' in a few hundred years, and that there is no substitute available when it has been depleted - unlike oil - then perhaps our view on Phosphorus should be a little more focused for the sake of our future.

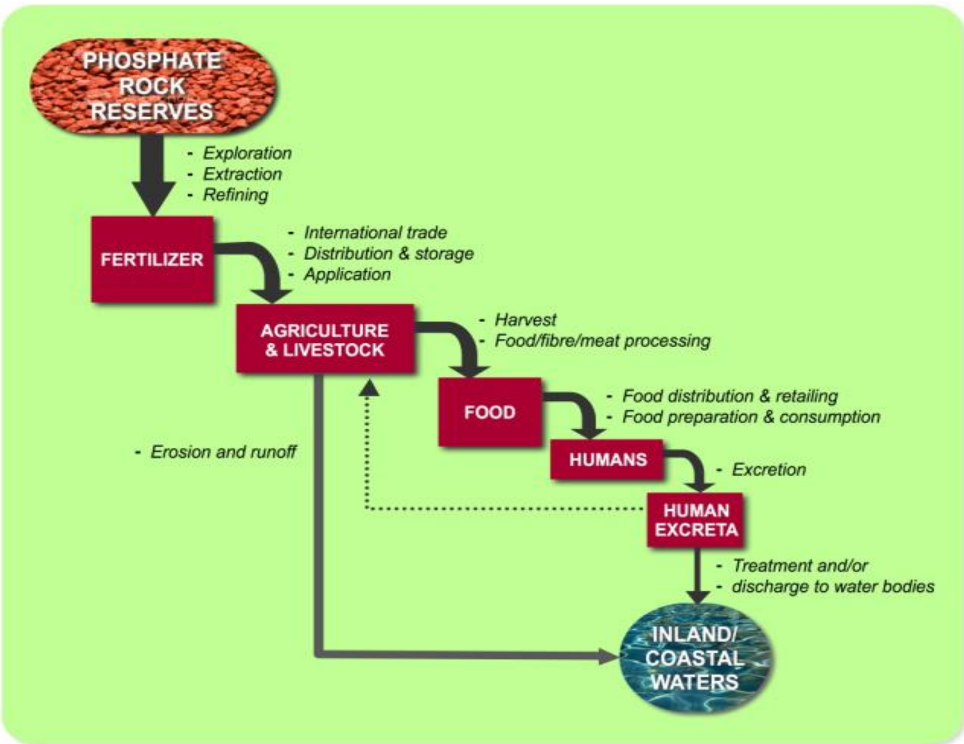
The importance of Phosphorus mirrors many other factors in our lives where the world population is heading towards 9 Billion in 2050 *(United Nations Population Fund 2011 http://www.unfpa.org/swp/),* as eating habits across the Eastern world change, and the challenge to farming over the next 50 years is to produce more with less. Historically, farming systems adapted to low Phosphorus fertiliser availability by utilising the Phosphorus present in animal wastes and green manures as much as possible. In addition, wastes were collected from human settlements and stables away from arable land, and brought to the arable land for its improvement. This Phosphorus collection was done all around the world and still happens today over large parts of it.

There has, however, certainly during the 'green revolution', been a fundamental shift away from this recycling of Phosphorus and other nutrients to the use of manufactured fertilisers. This disconnect has happened at many scales from local farm, to regional, country and to continental distances. The Phosphorus being used in one area is being transported, through produce, to be concentrated in other areas where the nutrient is being lost through the food and water systems. This has been driven by the process of specialisation of activity. It is certainly not unique to farming, as nearly all production and service industries are consolidated into factories or regions as is appropriate for low unit cost output. Farming has attempted to employ modern technologies and economies of scale for different farming systems in those regions where it has been most cost-effective to do so. In the context of the UK, we would recognise that arable systems by and large are operative in the east of the country, while the dairy livestock industry is concentrated on the land in the west.

In the UK, we are blessed with a generally forgiving climate, good soils, good access to our markets, well developed transport links for inputs and products, a skilled workforce, a stable democratic government system, security and good beer. Apart from New Zealand, which also shares these attributes - except for the beer - none of the countries I visited, or whose farming systems I studied can boast such a broad range of advantages.

It is with this knowledge that I write this report, knowing in my own mind that UK farming has a bright future providing we maintain these advantages. As an island without a mineable source of Phosphorus, and as a net exporter of grains, we do still however have the theoretical possibility of being over 70% Phosphorus-secure, provided we could use the existing Phosphorus sources with careful management and co-ordinated nutrient re-use technologies. This is not likely to happen in the near future. While imported Phosphorus fertilisers are cheaper than the systems required to re-use and recycle existing sources, manufactured fertilisers will continue to be used.

The other major factor is that the acceptability of recycled Phosphorus by consumers still raises many barriers to effective recycling of Phosphorus. Farmers will not change this public perception by themselves, but the importance of sustainable food production at all levels will only increase in the years ahead, and Phosphorus will be an important issue within this argument. To highlight these issues, below is a simplified illustration of the flow of Phosphorus, and its tendency to flow always in the same direction. *(Source:- Cordell, 2008)*



The requirement for systems to be developed to slow or halt the flow of Phosphorus ultimately into the seas can only rise over time.

4. Methodology, Contacts and Acknowledgments

This Nuffield Arden Scholarship was awarded jointly to Mark Tucker and me in the late spring of 2011. We have both studied under the same remit and subject title: **'Fertilisers for the Future'**. Our individual preferences were however to study different nutrients, and as highlighted in the introduction my choice was Phosphorus, while Mark aimed to tackle the subject with reference to Nitrogen.

It is perhaps relevant to note that the remaining major nutrient, Potassium, was never considered by either of us in answering the Arden Scholarship's call for looking at the 'Future of Fertilisers'. This is in my case because the nutrient has higher levels of reserves across the globe, and the efficient use of the nutrient is more widely understood and practised, certainly within a UK context. In addition, the environmental issues with regard to Potassium do not compare with the detrimental effects of excess Nitrogen and Phosphorus in the wider environment. It is through this lens, that Nitrogen and Phosphorus become the centre of attention.

Due to my work commitments during the harvest period, I was only able to conduct desk work and a couple of visits to experts before the middle of July. The access to vast quantities of data from around the globe via the internet makes finding relevant information difficult; however, the links with people that can be made through this medium shrink the world somewhat.

Main UK Institutions and Persons communicated with:

Chris Dawson, International Fertiliser Society, UK

Ian Richards, Fertiliser Advisor to BASIS UK

James Hutton Institute, Dundee:- Dr. Tim George, Prof. Phil White, Dr. Ron Wheatley

Bangor University:- Prof. Paul Withers

Nottingham University:- John Hammond

Harper Adams:- Grace Smith, Scott Kirby

Exeter University:- Katherine Garvey

Chris Rigley, Yorkshire Arable Marketing

Dr. Chris Green, Crop Management Information Ltd.

Cranfield University: Ruben Sakrabani

Lancaster University:- Prof. Phil Haygarth

Rothamstead Research:-Dr. Martin Blackwell.

My first trip abroad was in November 2011 to Canada to follow up on conversations via telephone and e-mail with the scientists who helped develop the first commercial Phosphate recovery from waste water streams. This led me further around Canada visiting those universities and research stations where Phosphorus is being studied. Indeed I found, when conducting my desk research, that the depth of expertise in this field was concentrated across Canada.

North American Institutions and Persons communicated with:

University Of British Columbia:- Don Mavinic, Victor Lo, Hui Zhang

Abbotsford Phosphorus Conference:- Andrew Sharpley

University Of Saskatoon- Dr. Jeff Schoenau

International Plant Nutrition Institute:- Adrian Johnston

AAFC Indian Head Research station, Guy Lafond, Jim Halford

AAFC Brandon Research Centre- Dr. Cindy Grant

University Of Manitoba- Don Flaten, Nazim Cicek, Christine Rawluk

Gerald Wiebe, farmer and soil specialist.

AAFC Swift Current Research Station:- Dr. Yantai Gan, Dr. Barbara Cade-Munun

AAFC Lethbridge Research Centre:- Dr. Francis Larney, Dr. Ross Mckensie,

On my return from the US and Canada, both Mark and I were asked to present our findings to date to the technical committee of the Royal Agricultural Society of England, in London in February 2012. This was a useful exercise for me and hopefully useful information for the committee also. It gave me the opportunity to assimilate the research up to that point and recognise those areas of the subject that needed further work.

Southern hemisphere visits:

A 3rd International Bi-annual Phosphorus Conference was to be held in Sydney, Australia, organised by the Global Phosphorus Initiative. The list of attendees included experts from across the globe with their disciplines ranging from Phosphorus mining, through recycling technologies to Plant Phosphorus Use

Efficiency. I attended this 3-day conference, from which I developed the opportunity to visit New Zealand and other parts of Australia.

This list of persons is too long to show in detail, but includes:-

University of Lincoln, New Zealand:- Prof. Leo Condron

Craige Mckensie, farmer of enormous wheat crops

CSIRO, Canberra, Australia:- Dr. Alan Richardson, Dr. Richard Simpson

University of Arizona:- Dr. Jessica Corman

University of Sydney:- Dr. Dana Cordell.

From the contacts made and from my own thoughts which were being formulated, I returned to James Hutton Institute to meet Prof. Phil White and Dr Tim George to develop a lasting legacy to this research project.

This report has been finalised in the weeks leading up to the presentation of our findings at an Arden Scholarship Conference, held at Harper Adams University on the 19th April 2012.

SECTION A :

The science behind Phosphorus Use Efficiency by plants

A1. Why Fertilise?

During the course of my studies, perhaps one of the more fundamental questions that I did not at first consider, but which is actually the basis of this work, was:

Why we as farmers use fertilisers of any type?

It may at first glance be a simple question to answer; however when considering the complexities of the production of commodities, the reasons for the use of fertilisers become more diverse.

Leibig's laws were produced by Prof. Justus von Leibig in 1840. They form the basic understanding of fertilisation in agriculture and are as relevant and important today as then. They are worth highlighting at this point:-

- A soil can be termed fertile only when it contains all the minerals requisite for the nutrition of plants, in the required quantity and in the proper form.
- With every crop a portion of these ingredients is removed; a part of this portion is again added from the inexhaustible store of the atmosphere. Another part is however lost for ever if not replaced by man.
- The fertility of soil remains unchanged if all the ingredients of the crop are given back to the land. Such restitution is effected by manure.
- The manure produced in the course of husbandry is not sufficient permanently to maintain the fertility of the farm; it lacks the constituents which are annually exported in the shape of grain, hay, milk and livestock.

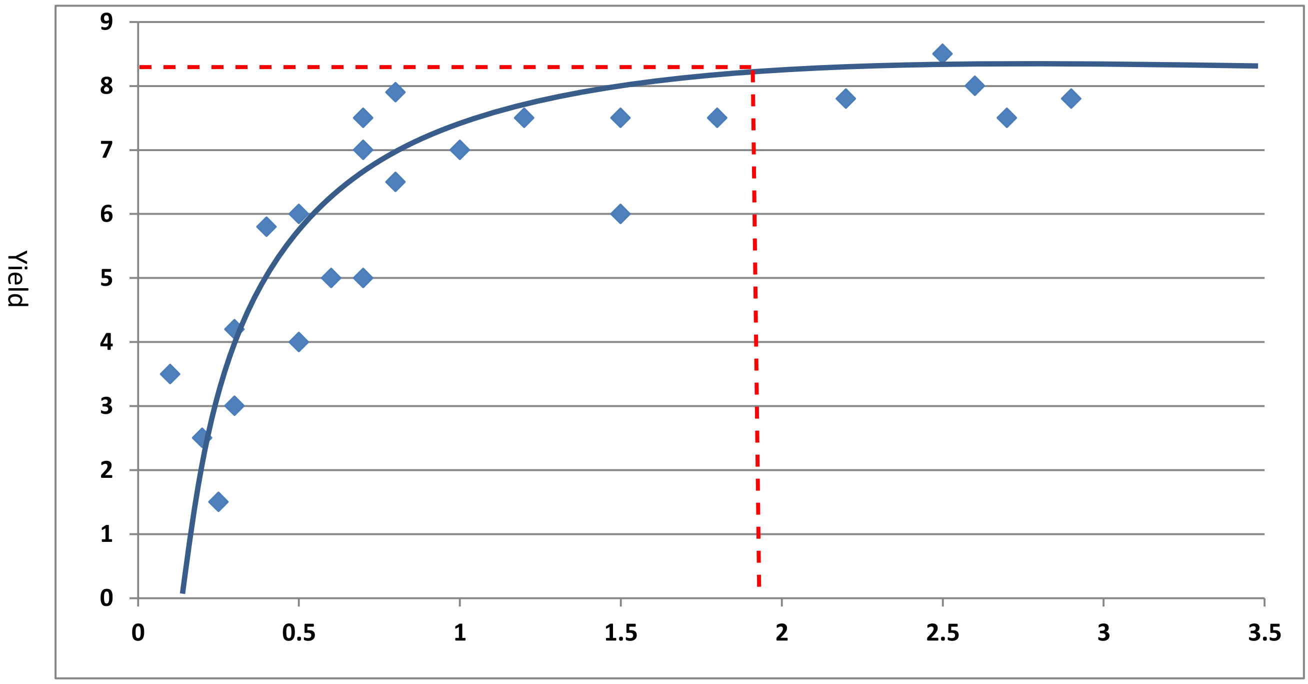
We should also include the wider physical factors that are included in the process of farming. The supply of water has the greatest single impact, but the distance of land to the market for agricultural produce, general climate, and climate extremes also play an important role in the decisions of where and what to farm. Politics, without expanding the subject further, should also have an impact on our choices as farmers in what we crop.

In essence we fertilise to REPLACE those mineral elements removed by harvested crops, and then to RAISE the capability of a given area of land to support the production of crops. However, this process should only be carried out where it produces an economic return to the farmer. It is easily said and understood that this is accepted good practice, but in reality the ability of an application of fertilisers to raise crop yield sufficiently to return an economic output is not always realised. We know that when cropping cereals in the UK, in most circumstances not applying Phosphorus and Potash in a single year will not result in crop failure. So we come back to the question of correct fertiliser application. Are the decisions to apply Phosphorus in UK farming systems based upon sound agronomic and economic reasons? At what price does Phosphorus become uneconomic against a given price for the crop?

A2. Critical values for Phosphorus

We, as farmers, understand that plants need nutrients, but the response to each nutrient, (assuming all others are in ample supply, Leibig's Law), is different. In my aim to study Phosphorus Use Efficiency (PUE) the first point of reference is to appreciate a crop's response to the supply of Phosphorus from deficiency through to oversupply.

The graph below shows the standard response curve to soil Phosphorus. This curve has been identified, illustrated and repeated many times across many different farming systems across the world. The figures across each axis may change, but the shape of the response and concept has remained robust across many different farming systems.



Index P

Source; Syers et al 2008

A2 (a) The problems with this model

A crop's response to soil Phosphorus varies with different field conditions, soil types and cropping systems, climate and other factors. The factors that affect Phosphorus uptake are so diverse, as will be explained later, that direct relationships across different soils and cropping systems are difficult to identify. The response curve above can be quite different in amounts along each axis for areas within the same field, cropping the same cultivar, but in different years.

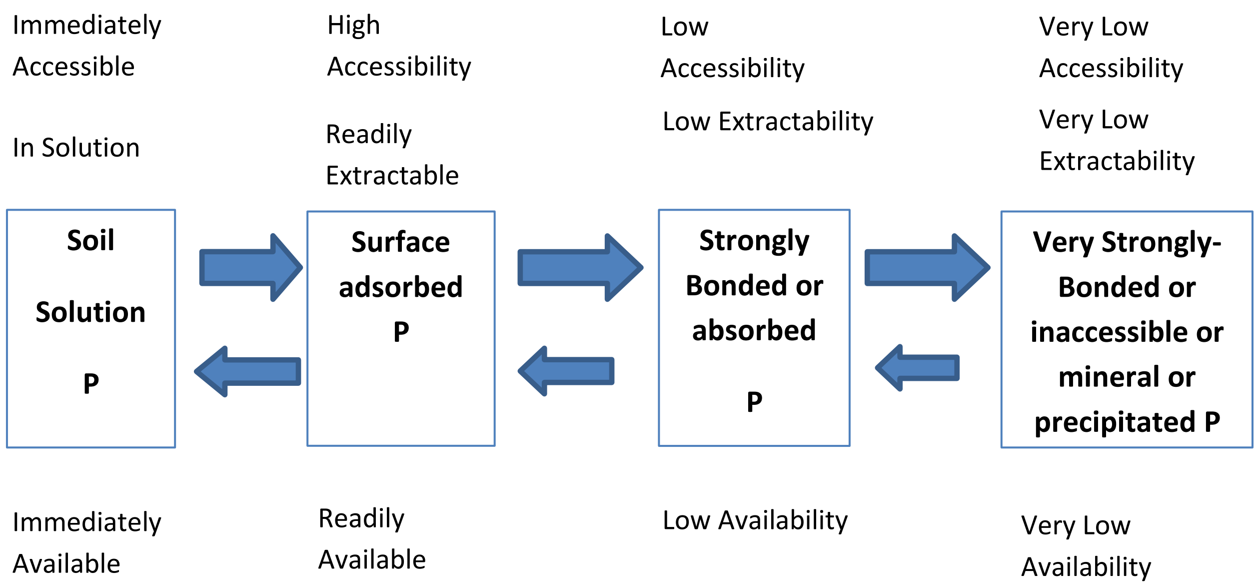
Therefore the specific target index for Phosphorus depends upon a wide range of factors, and the graph can be plotted against a number of differing measures for Phosphate availability. In the UK, we use the Olsen Test; however there are many other tests that are used to model the availability of Phosphorus across different soil and cropping systems across the world. An explanation of the tests available and the factors affecting the response curve above will follow. Before this however I want to discuss how Phosphorus behaves in the soil.

A3. The Theory of Phosphorus Pools

The basics of this theory come from the work done at Rothamsted in the UK. Experiments begun in the middle of the 19^{th} Century led to the recognition that more Phosphorus needed to be applied than what was removed by the crop in any given year *(Johnston 1970).* The requirement to find out where this Phosphorus had gone to was researched by Liebig in the 1870s alongside many others and it was widely found that 80-90% of the Phosphorus applied but not removed by the crop was still present in the surface layers of the soil *(Dyer 1902).* The need to discover whether this accumulated Phosphorus was ever utilised again became more important for financial reasons. When tenant farmers left their land after application(s) of Phosphorus fertilisers, should there have been a value returned to that tenant for the residual nutrition?

The recognition that Phosphorus once applied to soils was not irrevocably lost once it had been 'fixed' was highlighted by Kurtz *(1953).* He noted that *"Contrary to the apparent belief of two decades ago, more recent evidence indicates that for most soils the term fixation is an exaggeration".* The present view amongst scientists is described by Syers et al, (FAO, 2008). It highlights the fact that inorganic Phosphorus is more likely to be retained in the soil components with a continuum of bonding energies. In essence, there is a range of strengths with which Phosphorus is held by the soil and the stronger it is held, the less available it is to the plant. The idea is illustrated below.

Ref. Syers et al, (FAO 2008)



The evidence for this reversibility concept comes largely from the earliest and continuous work at Rothamsted. This has since been replicated across the world, and I visited Canadian, Australian, European and New Zealand research centres that have confirmed the longer term availability of Phosphorus.

Phosphorus is taken up from the soil in the form of orthophosphate ions. These are $H_2PO_4^-$ and to a lesser extent HPO_4^{2-}. The amount of Phosphorus found in the soil in this form at any given time, however, is extremely low. For reference, in a typical UK soil to a depth of 30 cm holding 6 cm of water, there will be less than 0.2 kg of P ha^{-1}. If a crop uses 37cm of water during a growing season, there will only be 1 kg of P ha^{-1}. The actual uptake of Phosphorus over this period however may be between 20-40 kg of P ha^{-1}, *(Syres et al 2008).* This happens because the plant has the ability to take up Phosphorus at very low soil solution concentrations, and as this process happens, the soluble Phosphorus fraction is replaced from the insoluble form. This is provided there is enough Phosphorus in the soil minerals or as part of organic material, which can be mineralised readily.

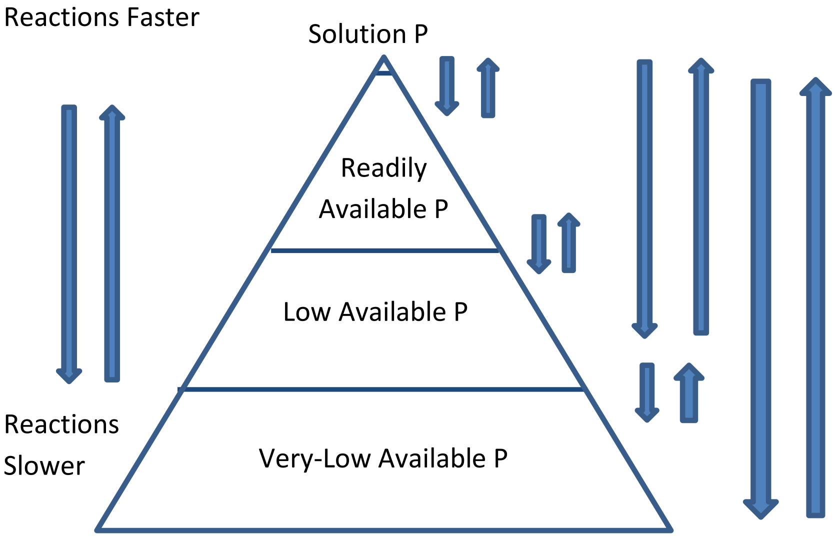
From the diagram on the previous page, Phosphorus in soil solution is immediately available for uptake by plant roots. The second pool represents readily extractable Phosphorus held on sites on the surface of soil components. This Phosphorus is considered to be in equilibrium with the Phosphorus in the soil solution and it can be transferred easily to the soil solution as the concentration of Phosphorus in the former is lowered through uptake by plants. The Phosphorus in the third and fourth pools represents Phosphorus that is more strongly bonded or 'held' to soil or present within soil complexes, and this can be referred to as absorbed.

I was impressed by an excellent explanation from Richard Simpson from CSIRO in Canberra, Australia, when he used the phrase that has stuck with me when describing the plant available pools of Phosphorus. He said that these pools represent the *'….working capital of the soil, in the same way that cash is the working capital of a business, and it is the concentration of plant available Phosphorus that determines productivity'.* With this monetary analogy, in the bank account of nutrients kept in the soil, you can make withdrawals and even run an overdraft, but ultimately the cash or Phosphorus has to be returned.

This model is widely used. However, I prefer to use the following model as I feel it better visualises the relative amounts of Phosphorus in each of the pools.

See next page : The Pyramid Concept

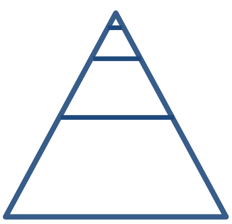
A3 (a) The Pyramid Concept



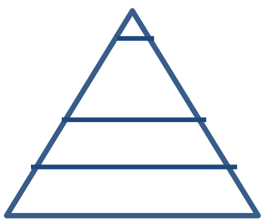
The movement of Phosphate through the 'Pools' does not necessarily flow in direct order. Phosphate can transfer from any pool in to any other, but the higher the pools the more rapid the change.

This pyramid aims to conceptualise the relative sizes of the differing pools of Phosphorus. The total area of the Pyramid for a UK arable soil could be in the region of 1500-3000 kg of P ha^{-1} ha of soil to 30 cm depth, but there may be as little as 0.2 kg of P ha^{-1} in the Solution Phosphorus fraction. From this illustration, it is clear that the bulk of the Phosphorus is in pools that are not immediately accessible by plants. The reactions that move Phosphorus through the pyramid are controlled by many factors, and these are happening all the time.

The problem with this model is that is it does not show that Phosphorus can move directly from any level in the Pyramid to any other. Adding water-soluble Phosphorus can be adsorbed or absorbed directly into all the levels over a short (10 day) period after application. The movement of Phosphorus through the different levels of the pyramid is controlled by the chemical, physical and biological characteristics of the soil. With these factors each having an effect, we can further our understanding of Phosphorus in this pyramid across different soils and cropping systems by seeing the Pyramid shape changing and the Pool boundary lines being moveable, as in the diagrams below.

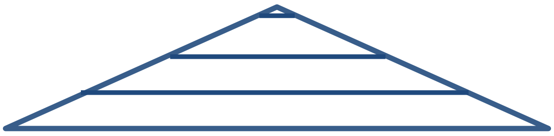


This soil may have a High ability to hold on to Phosphorus



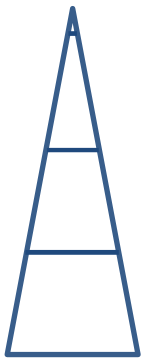
This soil may have a low ability to hold on to Phosphorus

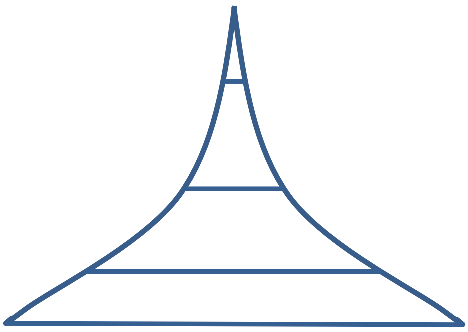
Likewise, the rate at which Phosphorus may adsorption, absorption and desorption could be described again in this pyramidal form by altering the shape of the model as shown below.



This pyramid may show the slower rate of changes in bonding strengths of Phosphorus

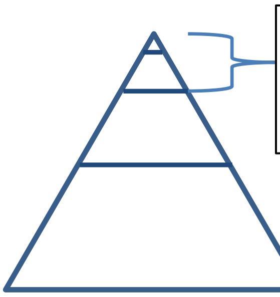
This pyramid may show the faster rate of changes in bonding strengths of Phosphorus





This curved pyramid may show the slower rate of changes in bonding strengths of Phosphorus when the nutrient is making the strongest bonds, but faster as the bonds become weaker higher up the pyramid.

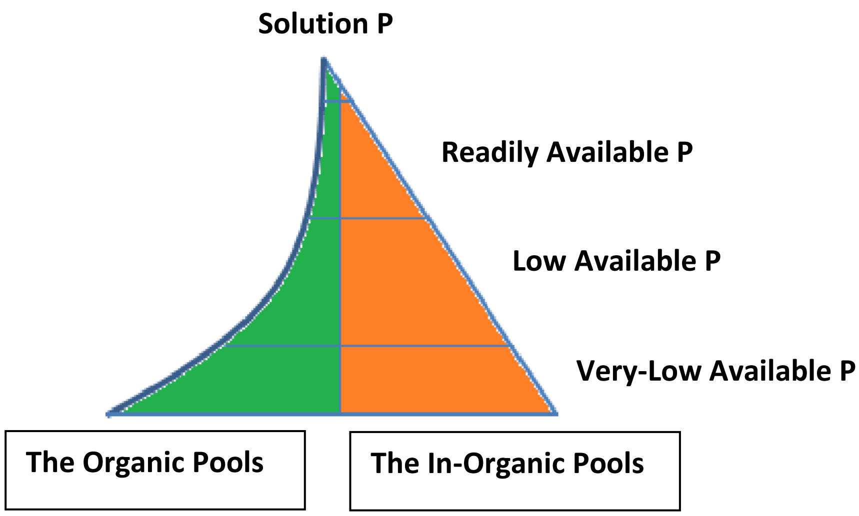
The processes of soil testing in the UK largely use the Olsen Test. This is discussed later in this report in more detail, but for reference at this point, and to understand which part of the pyramid is being measured, we can demonstrate that on this model, P-index according to the Olsen test measures the top 2 sections, i.e. the Soil Solution and the Readily Available portions.



This is the fraction generally considered to be measure by the Olsen Test.

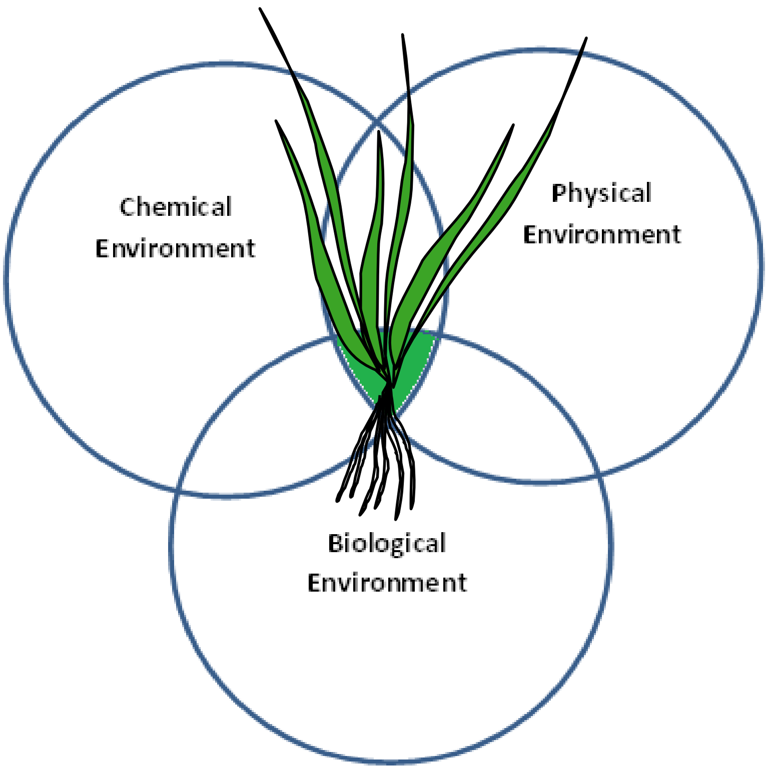
I have been made aware of variations to this explanation of the Olsen P Fraction where only 50% of the readily available pool is measured, but as the lines between the pools are conceptual only and there is a continuous variation in Phosphorus bond strengths or availability, I believe the argument is arbitrary.

The above Pyramids can be further extended to conceptualise the different sources of Phosphorus in organic and inorganic fractions. The processes through which Phosphorus must travel from solution to being strongly bonded can be very different for the organic and inorganic fractions of Phosphorus. The proportion of these fractions varies greatly from one soil type to another and the complication of different 'Pyramid shapes' combining, highlight the difficulty in expressing the transfer of Phosphorus through the Pools in a visual format.



A4. Factors that affect the availability of Phosphorus

There are many factors which affect Phosphorus in soils and the ability of plants to take up the nutrient. It is a question that arises many times, and from different angles, depending on the particular area of research you are looking into when considering PUE. I am again trying to conceptualise the factors in a diagram showing the different issues that affect PUE.



In this diagram, I have each circle the same size, and interacting with the other 2 in the same proportions. However different soils and different cropping systems would give rise to circles of varying size, and the interactions between each circle may again be in differing proportions with reference to Phosphorus availability.

1. **Chemical Environment**.

There are aspects in this sphere that can be changed at varying speeds plus those that cannot be altered by farming practice.

- pH. This is one of the simple factors that in certain circumstances can be changed by agricultural practice. The efficiency of Phosphorus uptake varies with pH.
- Fe/Al/Ca content of soil. These are largely controlled by underlying soil type and can strongly affect the ability of soil to hold Phosphorus in the various Pools and in varying total amounts.
- Total Phosphorus levels. The 'size of the Pyramid' will affect the level of Phosphorus saturation of the soil, and therefore the rate at which the Phosphorus will transfer between the pools and in which general direction.

- Supply of other major nutrients. These will affect the inorganic and organic processes occurring in the soil which influence the movement of Phosphorus
- Supply of secondary micronutrients. Again these will affect the inorganic and organic Phosphorus processes that happen in the soil which influence the movement of Phosphorus
- Supply of Carbon. This will have a particular effect on the organic cycling of Phosphorus, depending upon the source of carbon.

2. Physical Environment

These aspects can be more generally controlled by agricultural management.

- Soil structure. Soil Structure affects the ability of plants to root in a way which allows access to the nutrients present in the soil. It may also maintain and enhance the environment for micro-biota to sustain and improve the processes which are related to systems involving plants' access to Phosphorus.
- Organic Matter. This affects the balance between the supply of Phosphorus in the Pools from organic and inorganic sources. It is necessary to maintain the environment for micro-biota to survive and thrive and create a healthy soil.
- Aeration. As a result of a well-structured soil, aeration will maintain the aerobic respiration of living organisms in the soil, which is preferable to anaerobic respiration for the general health of the soil.
- Water saturation level. In conjunction with soil structure and aeration, sufficient moisture is required for the micro-biota to function efficiently, and for the inorganic chemical process to work efficiently.
- Temperature. A frozen soil will have little to no organic activity and inorganic processes are reduced

3. Biological environment

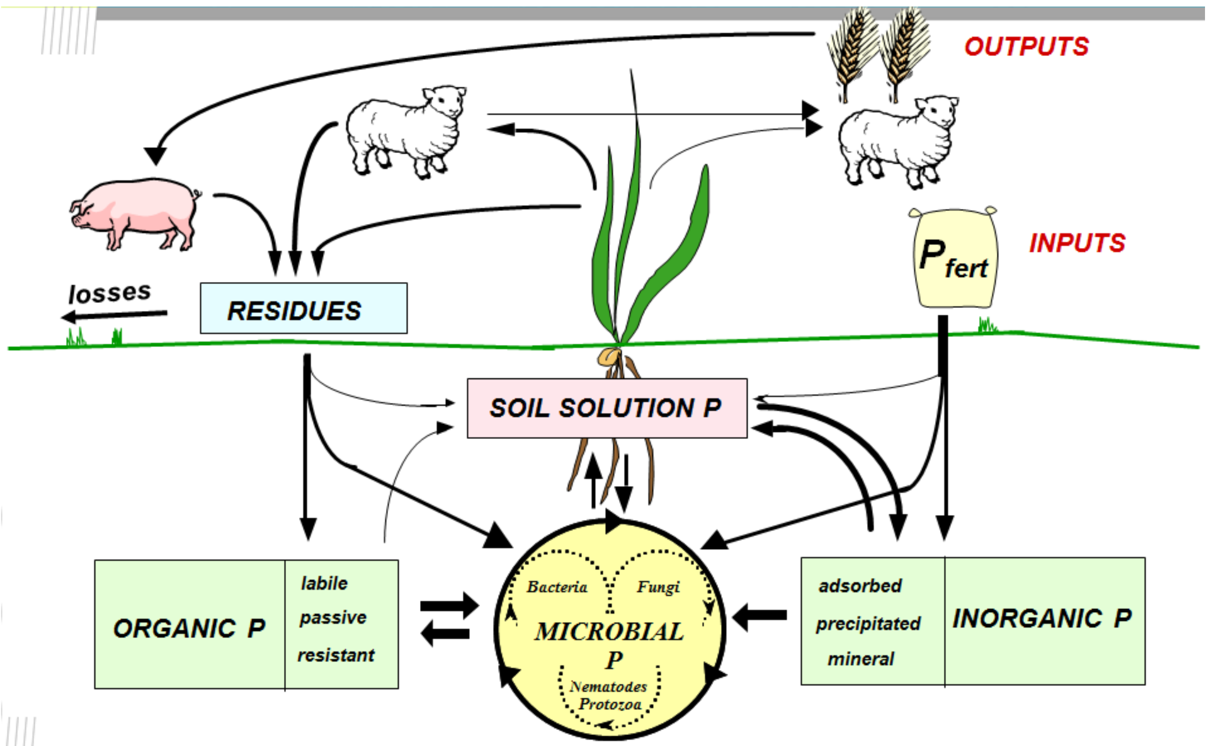
Soil Biota can be encouraged or otherwise affected by controlling the physical and chemical environments. The study of the biological environment is extremely complex and extends far beyond this discussion. The activity of micro-biota is discussed specifically later in relation to specific species effect on PUE. For now a list highlights the broad spectrum of biological effects:

- Bacteria
- Fungi
- Nematodes
- Worms

A5. The Phosphorus Cycle

We need to recognise the flow processes through which Phosphorus passes to recognise the vastly different forms in which this element can be found and in which it is required.

The illustration below does not show figures for quantities of Phosphorus, as they would be specific for each farming system, but the model is comprehensive for farming systems across the globe.



Model adapted from A.E. Richardson 2011.

This cycle for Phosphorus in agriculture shows the separate sources of Phosphorus and highlights the types of Phosphorus in the system.

A6. What is Phosphorus Use Efficiency (PUE)?

This can be described simply as producing the maximum amount of output/yield, for the minimum amount of Phosphorus removed from the soil.

The extrapolation of this definition, however, would tend to a point where crops did not remove any Phosphorus when removing the produce and this is clearly not achievable or desirable. The product of the field must contain some Phosphorus to supply the consumer, animal or human, with the desired level of Phosphorus nutrition.

The process of looking at plant PUE can be broken down in to two distinct parts, to help us define those areas which we can try and understand:-

1. Utilisation efficiency or internal efficiency. This is the ability of the plant to convert absorbed Phosphorus into plant product/yield (root, tuber, shoot or grain). This will give a yield per unit of Phosphorus absorbed and can be measured. Different plants can produce more with less, within given extremes. We do need, however, to maintain the desired amount of Phosphorus in the harvestable portion to supply the required Phosphorus nutrition to the consumer of the harvest.

2. Uptake efficiency or External efficiency. This is a measure of the ability of a plant to acquire Phosphorus from a soil with different Phosphorus resources. Clearly some plants are better at acquiring Phosphorus from soils with lower concentrations of Phosphorus than others. The complication here is that the activities of plants in accessing greater quantities of Phosphorus do not necessarily result in increased production or yield. This can be as a consequence of the energy expanded in the process of enhancing Phosphorus uptake which diverts energy that might otherwise be used to increase yield.

A6 (a) How do we measure PUE?

We need to understand the reasons why the calculations that we use to measure PUE may be different to those calculations that we use for other nutrient efficiencies. We cannot, for example, use the same calculations for Phosphorus as we do when calculating the efficiency of Nitrogen. This is mainly due to the fact that the residual fertiliser Phosphorus not used in any given year does have a value in subsequent years. This would not be the case for Nitrogen.

The results given when quoting efficiency are usually in percentage terms and are meant to show a figure of fertiliser use against the amount found in the yield produced.

There are a number of methods for measuring efficiency *(Syers et al. 2008)* which I will list and describe accordingly:

1. **The Direct method**

This is the process where the exact level of fertiliser added is measured in the harvested yield and the percentage content calculated. This is extremely difficult to do, and requires the use of radioactive isotopes to 'mark' the fertiliser, which can then be tracked from the fertiliser into the produce. The half-life of P^{33} is unfortunately short at 25 days, so experiments over many months are difficult to carry out and are extremely expensive. Typically with Phosphorus for cereals, only 10-25% of the total amount of Phosphorus in the crop harvested is found to have originated from the specific application of fertiliser *(Mattingly, 1957).* This recovery percentage can also vary greatly with Phosphorus type, application system, soil type and crop cultivar. This is clearly not appropriate as the plant has not necessarily been deficient in Phosphorus as it has found other sources beyond those supplied by a particular application of fertiliser.
Verdict:- Not useful, unless your agenda is to restrict Phosphorus fertiliser use generally.

2. **Difference method**

This is where the increase in yield, or nutrient uptake, is compared across areas where fertiliser is and is not applied.

For example % P Recovery = $\dfrac{\text{P in Crop given P } \textit{minus} \text{ P in Crop without P}}{\text{P Applied}} \times 100$

Many factors have a direct effect on the result of the example, not least of which is the base level or residual Phosphorus present in the soil. The theory of the critical level, as discussed earlier, will greatly affect the perceived efficiency percentage. Where residual Phosphorus levels sit at the lower end of the curve, efficiency will be measured more highly, but at the cost of restricted yield. As the soil is higher up the curve towards the top, perceived single year efficiency may be low, but yields will be higher.
Verdict:- Not appropriate for a single year efficiency calculation.

3. **Balance method**

This calculation does not consider the variation between the uptake of Phosphorus by the crop on different areas where Phosphorus has and has not been added.

For example % P Recovery = P in Crop/P applied x 100.

This usually shows an increase in the percentage recovery, as farms today tend to only apply 'replacement' levels of Phosphorus.
Verdict:- More relevant, but needs to be considered in conjunction with soil tests. Any figure above 100% clearly shows that residual Phosphorus is being used by the plant, hence the reserves are going through a process of depletion.

Clearly the values that can be calculated by the three methods above can be very different. The problem with all these methods is that the recovery of added Phosphorus as measured in the yield is subject to such a wide range of factors from specific crop grown, weather, disease, rotation, to soil conditions.

The further analysis that needs to be done in conjunction with the methods above is to consider soil analysis. If we can identify and quantify that Phosphorus which has been added during the addition of fertilisers or manures, we can further assess the PUE levels.

A6 (b) Soil testing of Phosphorus

A variety of methods are available to measure the amount of available Phosphorus in the soil. Below is a shortened list of the main tests used across the world. The range of tests in itself should highlight the difficulty in producing a single test which is useful across the world for all crops in all soils. A simple water soluble Phosphorus test would not accurately represent the amount of Phosphorus that a plant may be able to access during a growing season even though this is the only form that a plant can take up. Therefore, a test which can quantify the 'available' Pools of Phosphorus from a particular soil is required. As discussed, Soil Phosphorus exists in several chemical forms in the soil. This includes both inorganic complexes (with calcium, iron and aluminium) and organic forms. The immediately available Phosphorus in the inorganic form occurring in the soil solution is orthophosphate. Other inorganic forms are largely unavailable although changes in pH can render some available. Many organic forms of Phosphorus are potentially available, and these are the main source of orthophosphate other than direct fertilisation with soluble phosphate. The aim of all the following tests is to measure the Phosphorus available to the plant:-

Olsen (sodium bicarbonate): This is the most commonly used test in the UK and extensively throughout the world. It was developed in 1954 by S.R. Olsen as a complementary procedure to the commonly used Bray P1 method at the time. It is a bicarbonate extraction (30 mins.) at pH 8.5. As with all tests, there are issues and limitations which include an underestimation of plant available Phosphorus following recent lime application or historical use of Reactive Phosphate Rock (RPR) fertiliser and over-estimation of Phosphorus in low pH soils and high Phosphorus Retention (ASC) soils. It provides a method of determining soil Phosphorus in alkaline soils where the Bray P1 method is unsatisfactory. Olsen-P gives a numerical result that is much smaller than the Bray P1 test and must be evaluated with its own calibration.

Colwell: This is a test widely used in Australia and based upon the Olsen method, but it has a longer extraction time. This is an attempt to show that fraction which is available from soils which tend to be more deficient in Phosphorus than other soils.

Bray P1: This method was developed in 1945 by Bray and Kurtz. The Bray P1 test is best suited to acid soils with a moderate cation exchange capacity, CEC, and base saturation, and organic soils. In soils with a pH above 7.2, the Bray P1 test may significantly under-estimate the amount of available Phosphorus.

Bray P2: This method was developed in 1945 by Bray and Kurtz. The Bray P1 and P2 extractants are the same in most respects, except that the hydrochloric acid in the P2 extractant is four times stronger than in the P1 extractant. The reason for the stronger acid in the P2 test is to extract additional soil Phosphorus that exists as tricalcium phosphate. This form of Phosphorus is not available to plants, and will not become available in the near future. At the time the P1 test was developed, farmers were applying large amounts of rock phosphate (tricalcium phosphate) to fields. The stronger P2 test provided an indication of the applied rock phosphate, even though that P was not available to plants. Today, few agronomists use this test to develop fertiliser recommendations.

Mehlich 1: This method was originally introduced by Dr. Adolf Mehlichin 1953 as the North Carolina Double Acid method. It is best adapted to the coastal plain soils of the Eastern U. S. The method was subsequently renamed the Mehlich 1 method, after Dr. Mehlich developed additional soil analysis methods. The method is in use by several laboratories in East Coast States.

Mehlich 3: In 1984, Dr. Adolf Mehlich introduced the procedure now called the Mehlich 3 test. There was a Mehlich 2 procedure between numbers 1 and 3. However, this test was found to have problems and was not adopted by laboratories. The Mehlich 3 method has proven to be very efficient and well correlated with other methods, and is fast becoming the most widely used extractant for agricultural tests. It is well correlated with the Bray P1 test (r^2 = 0.966) on acid soils, and on alkaline soils it is well correlated with the Olsen method (r^2 = 0.918).

Morgan: The original method was introduced by Morgan in 1932. A modification of the original method is also in use. Morgan and modified Morgan are used by a few University labs in New England and the Pacific Northwest. Both the original Morgan and the Modified Morgan are acceptable for a wide range of soil conditions. The Morgan methods tend to give very small numerical results compared to some of the other methods. The small number of labs using these methods limits their influence and usefulness on a widespread scale. Recent work at Cornell Univ., (NY) has developed a method of correlating Morgan P results with those of Mehlich 3.

Resin P: This is a water extraction at field pH using an ion exchange membrane to 'extract' Phosphorus from solution as it becomes solubilised. A limitation is that there is much less interpretive information available for the Resin P test.

Ammonium Bicarbonate-DTPA: First proposed by Soltanpour and Schwab in 1977, this method is used by a small number of laboratories. The method is highly correlated with the Olsen method for Phosphorus.

A6 (c) Interpretation of Soil Phosphorus tests

As highlighted above, each test aims to represent the plant-available Phosphorus for a given soil. With the wide variation in soil types across the globe and different cropping systems being farmed across each, the tests have developed accordingly. It should be recognised that each test will have inherent limitations in measuring the actual amount of plant available Phosphorus throughout the growing period. The ability to interpret soil Phosphorus test results requires an understanding of the inherent limitations of the test method and then the consideration of other information including soil pH, soil type, soil structure, fertiliser and production history alongside cropping species. Rotational soil sampling and yield monitoring at various scales can allow the farmer to see whether current practices are causing available Phosphorus levels to increase, decrease or remain static. The specific levels are not necessarily as important, assuming that Phosphorus is not the limiting yield factor from one season to the next, but rather the trend. It should be remembered that the soil test result represents the concentration of nutrient in the soil as sampled; so where the plant root zone is deeper than the sampling depth, the soil test may under-estimate available nutrients on a per hectare basis.

The importance of sampling in a consistent manner for test results to be comparable should not be under-estimated. When we consider the activity of Phosphorus in the soil over a growing season, during which time Phosphorus may be added, collecting the samples at the same time of year, to the same depth using the same spatial variance techniques, should be of the highest importance.

The purpose of the Phosphorus soil test for low Phosphorus soils is to provide a basis for calculating the capital fertiliser requirement to increase the Phosphorus status of soil, or if soil Phosphorus is high to give confidence that a 'less than maintenance' fertiliser application may be appropriate to achieve economic or environmental benefits.

A6 (d) How much Phosphorus should we be applying?

The simplest way of describing this where soil indexes are at adequate levels for required yield is as follows:-

$$P_{Fertiliser} = P_{Export} + P_{Erosion/loss} + P_{Waste\ Dispersal} + P_{Soil\ Accum}$$

Where:-

$P_{Fertiliser}$ = the amount of Phosphorus required to be added,

P_{Export} = removal of Phosphorus in products,

$P_{Erosion/loss}$ = Phosphorus lost by leaching, runoff or soil movement,

$P_{Waste\ Dispersal}$ = Phosphorus accumulated in small areas of farms as a result of uneven dispersal of animal excreta (in livestock systems),

$P_{Soil\ Accum}$, = Phosphorus accumulating as sparingly soluble phosphate, or organic compounds.

The key for PUE is to limit the factors above to a simple $P_{Fertiliser} = P_{Export}$ equation where possible through careful management. The key is to recognise those factors that can be reduced in an economically viable manner.

The problem with the equation above however is that it is rarely achieved or achievable except where the farming is under very low inputs systems, and hence low production *(McIvor et al 2011),* or in productive agriculture on soils that have an intrinsically low Phosphorus buffering capacity, or where Phosphorus buffering capacity is low because sorption sites for Phosphorus are close to saturation and soil fertility is relatively high, *(e.g. Syres et al 2008).*

Within a UK arable system the ability to maintain soils with Olsen test levels that provide a specific soil's critical value for Phosphorus is, as a minimum, the basic aim.

A7. Strategies to improve PUE

It is important to note that PUE must address the need to reduce the rates of Phosphorus loss, export and accumulation if significant changes are to be made.

Plant + Microbial Strategies for increasing PUE *(adapted from Richardson et al. 2011)*

i) Root foraging strategies:- These aim to improve the acquisition of soil Phosphorus, with the result of relying on lower critical Phosphorus levels for the desired production level.

ii) Soil Phosphorus 'mining strategies':-These aim to enhance the desorption, mineralisation and solubilisation of Phosphorus from the sparingly soluble Pools of Phosphorus *(Lambers et al 2008).* Mining Phosphorus from soils is not sustainable over the long term without replacement, but the aim of this strategy can be to increase the turnover of Phosphorus from the less available Pools and thus slow the gradual but net accumulation of Phosphorus that can occur in moderate to high Phosphorus sorbing soils. This would in effect result in the critical level being lowered.

iii) Plants with improved 'internal Phosphorus use efficiency':- These plants would be able to produce a greater yield per unit of Phosphorus uptake and could directly reduce the amount of Phosphorus required for production.

Within a UK farming context, we largely aim to maintain the overall fertility of the soil with regard to Phosphorus around an index 2. Should the mining and foraging strategies be used to lower the critical value, this would only give a one-time efficiency boost. As when Phosphorus inputs are reduced, and the new, lower critical value has been reached, Phosphorus inputs that match Phosphorus exports would have to be resumed at least in balance. So a system of improving plants' use of Phosphorus or reducing the levels of Phosphorus exported in crops provides the only prospect of increasing PUE.

A7 (a) Foraging for Phosphorus through changes in rooting characteristics

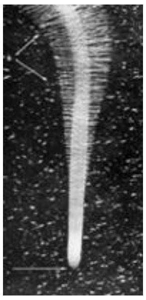
Studies have shown that there is a wide variation in the structures of roots in different plant species, and that this has a major impact on the plants' ability to acquire Phosphorus. *(Lynch, 2007).* This is not outside the realms of common sense; however, the control of rooting architecture is complex. Work on maize shows that a genetic propensity to produce increased and sustained lateral roots under Phosphorus deficiency, resulted in up to 100% greater Phosphorus accumulation than closely related genotypes with less lateral branching. *(Zhu and Lynch 2004).*

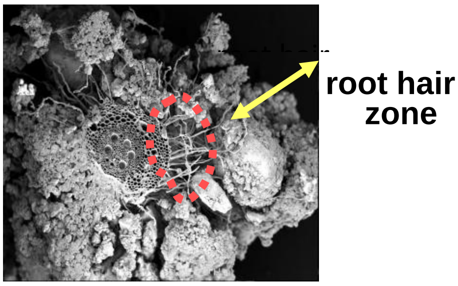
A picture taken of a tree plant growing on a rock wall, by the side of a main road near central Sydney. How is this plant accessing its Phosphorus?

When I have discussed the history of breeding programmes with wheat in a UK context, time and again it appears that breeders have, unsurprisingly, concentrated on 'above ground yield'. Within breeding programmes, soil supplied nutrition has not often been a limiting factor in selecting lines from which to select new varieties. The consequence of this has been the breeding of varieties that have perhaps lost the genetic potential to scavenge efficiently for all their nutrients, especially Phosphorus.

A7 (b) Root hairs

Root hairs are extremely important in the uptake of Phosphorus by plants, especially nutrients like Phosphorus that are poorly mobile. This has been proven by extensive work over 20 years, *(Gahoonia and Neilsen 1998, Bates and Lynch 2000*). The hairs have the effect of extending the surface area across which to take up P in to the rhizosphere.





The ability to select plants with longer root hairs is therefore an attractive prospect for having a direct impact on PUE. Work at James Hutton Institute in Dundee is looking at this very aspect with barley and wheat varieties. The ability to use marker-assisted breeding techniques should mean that once the genes/alleles, which affect root hair length, number and distribution, are identified they can be introduced through conventional breeding programmes.

> **A. Free Phosphorus lunch?**
>
> As with all things, there is always a trade off, and the allocation of the plant's resources to produce extra root hairs etc., represents a cost to the plant which in turn will affect yield. This is a theme which will recur ahead. However, the cost to the plant in producing extra root hairs is thought to be minor compared to the greater PUE. *(Bates & Lynch 2000).*

A7 (c) Arbuscular Mycorrhizal (AM) Symbiosis

A favourite topic along my travels has been the subject of how Arbuscular Mycorrhizal (AM) fungi can influence PUE. This subject has taken on an almost mythical state, whereby if only we understood the interactions better, and as farmers we could enhance and develop this symbiosis with plants, then all our problem would be solved……………….!

For early clarity, my own opinion is that the 'Jury is still out', especially when I consider the fungi's use in a UK context.

Plant and AM fungi symbiosis is the process where two organisms live together to the benefit of each other. AM fungi colonise most agricultural species, exceptions including the Brassica and Lupinus genera, and make an important contribution to the uptake of Phosphorus, especially on soils with low Phosphorus availability. This advantage, however, is lost where soil Phosphorus levels are at or near the point necessary for maximum growth. *(Schweiger et al 1995).*

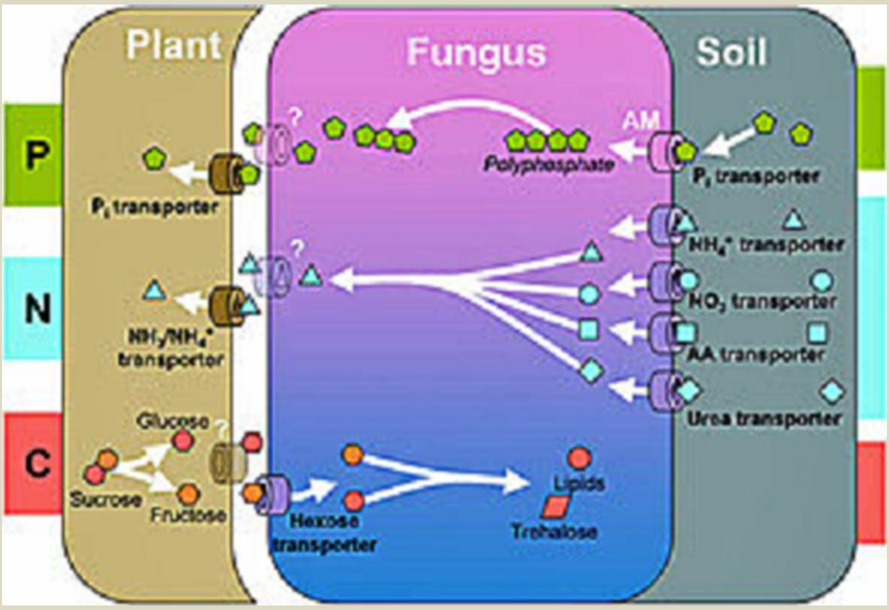
The AM fungi work by extending their hyphae network outside the root cell which they colonise, into the surrounding rhizosphere and beyond. This can be centimetres away from roots, whereas root hairs only extend millimetres *(Smith & Read 2008.)*

> **B. Free Phosphorus-Lunch?**
>
> The decline in positive AM fungal growth where available Phosphorus increases, and the decreasing proportion of colonised root length, may mean that the plant suppresses colonisation. If the symbiosis was always advantageous, then this response would not be expected. It is when we look at what the AM fungi get in return where we see a change from a symbiotic relationship, to one of a parasitic one. The AM fungi receive, in exchange, 'food' or carbon. It has been estimated that up to 20% of all photosynthetically fixed carbon might be delivered from a plant to the fungal partner.
>
> *contd. on next page*

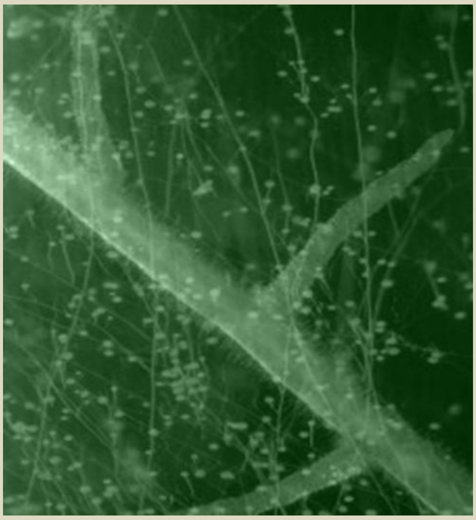
This diversion of photosynthetic production to the roots and the AM fungi reduces the available food to be stored in the grain. Therefore there is a yield penalty for encouraging AM fungi colonisation.

The difficulty in readily culturing and reproducing specific species of AM fungi has held back the possibility of large scale inoculations. This has delayed development of the use of these in appropriate cropping situations, i.e. (very) low Phosphorus soils. Commercial strains are however available and are discussed later.

The illustration below aims to show those process and transfers of nutrients that are affected by AM fungi.



This picture shows the fine structure of the AM fungi hyphae that extend from the roots of a plant.



A7 (d) Exudate production by roots to desorb/mobilise sparingly soluble Phosphorus

This can be further broken down in to two areas:

1. Exudation of anions.
2. Exudation of enzymes.
3. A combination of 1 and 2

1. Exudation of anions

This is the process whereby plants exude anions through their roots. These anions are negatively charged molecules, in the form of citrate, malate or oxalate and have been observed to be secreted by certain plant species. It is thought that the production of these organic anions can improve Phosphorus nutrition by mobilising sparingly soluble pools of inorganic Phosphorus into the soil solution. The anions are thought to occupy sorption sites on soil minerals that might otherwise bind Phosphorus, or displace and replace Phosphorus in the sparingly soluble pools that would otherwise form with aluminium, iron or calcium.

This has come from observations of increased exudation from certain species where Phosphorus has become deficient, *(Jones 1998).* Attempts have been made to genetically modify plants to produce more anion biosynthesis and exudation. This paper is not the place for a thorough discussion on this particular science, but suffice it to say that with the exception of trials with tobacco plants *(de la Fuente et al 1997),* where Phosphorus uptake was increased and corresponded with increased yield, a direct positive yield link has yet to be proven. This is due to the fact that production of the anions is only part of this system. The transport of the anions across the root membranes is key to the delivery levels of anions found in the rhizosphere, rather than the actual levels of anions produced.

2. Exudation of enzymes

The cycling of the organic portion of the Pools of Phosphorus can add significantly to the Phosphorus supplied to a plant during its life cycle. This is particularly important where the added sources of Phosphorus come from large amounts of crop residues returned to the soil, or the addition of manures. The addition of inorganic sources of Phosphorus can also add to the organic pool as readily available inorganic Phosphorus is accumulated into organic sources by microbial activity *(Richardson and Simpson 2011).*

The cycling of Phosphorus from organic forms into plant available forms is, I believe, one of the main influences that farmers can have on the availability of Phosphorus. The supply of organic source Phosphorus can be affected by management, e.g. green manuring, addition of extra organic matter, soil structure management, pH, aeration, moisture control etc. Mineralisation of organic Phosphorus occurs through the activity of phosphatase enzymes which break down the complex forms of Phosphorus contained in organic matter into fractions which include orthophosphate, the plant available source of Phosphorus. The production of these enzymes is not confined to plants, however, as microbes also have the ability to produce phosphatases. It was proven many years ago that plants can effectively use the Phosphorus from these organic mineralisation reactions. *(Adams and Pate 1992)*

In most cases where increased root phosphatase activity has been identified, the plants have been reacting to a Phosphorus deficiency. The production of these enzymes is proposed to not only increase the mineralisation of rhizosphere organic Phosphorus, but to enhance the internal recycling of Phosphorus, and the recovery of organic Phosphorus that may be lost by plants as other exudates are released by the roots. *(Duff et al 1994).* There are, however, few instances where this interaction produced field replicated results for increased Phosphorus utilisation, where phenotypes selected for their increased phosphatase activity have been used. *(George et al 2008).*

3. The combination of 1 and 2

This is one of the many instances where the complexity of Phosphorus is highlighted. The availability of organic anions in the soil enhances the mobility of organic Phosphorus. This Phosphorus can be then more effectively interacted with the presence of phosphatases, such that greater levels of Phosphorus can be mineralised *(Wei et al 2010).* Further work in this area of the science is required to understand these interactions.

C. Another Free Phosphorus lunch?

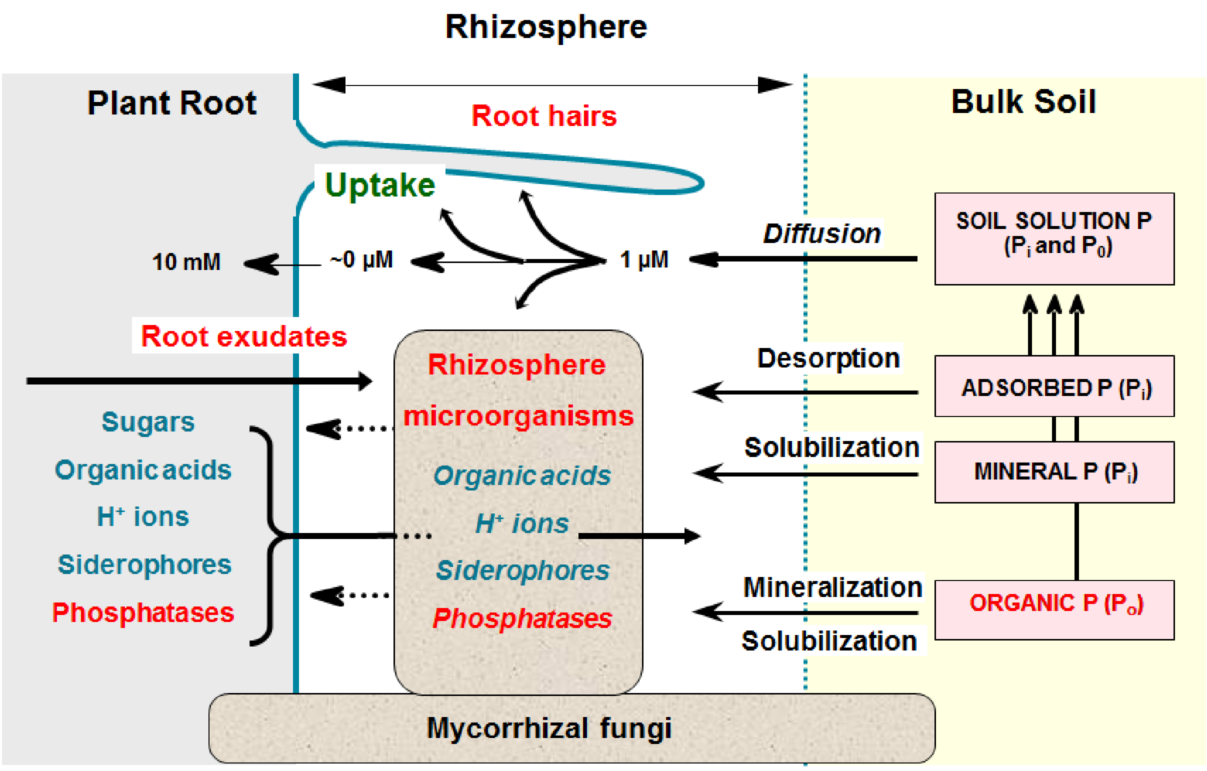
Again to repeat the comments above, the process of plants producing anions and enzymes takes photosynthetic products to produce them. The production of carbon products fed through roots and used by micro-biota which also have the ability to produce Phosphorus mineralising enzymes is an additional trade-off. The cost-reward relationship is not thoroughly understood in this area.

A7 (e) Microbial Inoculations

Bacterial and fungal activity in the soil are known to play an integral part in the cycling of both organic and inorganic Phosphorus in the rhizosphere and beyond in the general soil profile. Commercial products have been available in North America for many years, and have now become available in the UK and other countries worldwide.

The strains produced are generally specific species of Penicillium or Aspergillus *(Relwani et al 2008, Whitelaw et al 1999).* These produce organic anions, protons, phosphatases and chelating compounds which release orthophosphate from soil mineral surfaces or from breaking down organic sources of Phosphorus. The difficulty in using these inoculants is that the specific strains can be difficult to identify for each soil and cropping situation. There is also the need to develop reliable delivery systems to successfully inoculate the rhizosphere and ensure the survival of that inoculant. Their ability to then multiply successfully and colonise the soil is key to their success.

The following diagram is a schematic I was given by A.E Richardson in describing all the process described above which are used by the plant in the uptake of Phosphorus.



A7 (f) Soil Fauna Diversity

Within different soils, there are vastly different ranges of living organisms ranging from bacteria and fungi to invertebrates. These survive on a diet of exudates from plant roots, organic matter, or from feeding upon different other species of living organisms. The activity of all of these together can have a dramatic effect on the cycling of organic source of Phosphorus, by both immobilizing as well as mineralising sources of Phosphorus. There have been, over a number of years, various studies that have looked at whether the diversity of different soil organisms affect the processes in the soil, including all types of nutrient cycling, not just with relation to Phosphorus. *(P. Haygarth et al. 2011).* Some have shown evidence for different combinations of species that can have a positive influence on the decomposition of organic matter. However, these effects mostly occur at the low diversity end of the diversity spectrum, and at levels of diversity that are likely to be well below that which is found in real ecosystems (*Wardle, 2002)*. There is also evidence that the diversity of ectomycorrhizal fungi and AM fungi can affect plant growth, with responses ranging from positive to negative. The overall message that comes from the conclusions of these studies is that the diversity of species present is not as important as the changes in the number of a specific species and their activity and interactions.

A7 (g) Internal Phosphorus Use Efficiency

With the aim of improving overall PUE, the ability of plants to use the Phosphorus that has been taken up efficiently is key, otherwise the effort that has been invested by the plant and the farmer in supplying the required level of Phosphorus has been wasted to some degree.

In my travels, it has been difficult to find successful systems being developed to increase internal PUE, much of the work to date being on the external PUE, i.e. the efficient uptake of Phosphorus from soil by plants. I will try to explain a reason for this in relation to attempted breeding programs - it is a slightly awkward concept to understand.

The ideal plant would be one that efficiently extracted Phosphorus from low Phosphorus containing soils while, at the same time, being able to use that Phosphorus by producing more biomass per unit of Phosphorus taken up. The problem arises when, as the Phosphorus level in the soil increases, so do tissue concentrations of plants grown in that increased Phosphorus soil, effectively leading to a lower internal PUE. It also follows that those plants, under Phosphorus deficiency, exhibit traits that increase uptake efficiency, therefore absorbing more Phosphorus and negating the need to evolve systems to improve internal PUE. It has been suggested, by *Rose et al 2011*, that in soil conditions internal and external PUE are inextricably linked. So it has been very difficult to identify those genotypes which show internal PUE with no detriment to yield.

It is clear that there is a requirement for future studies on this subject to identify the genetic aspects of a cultivar which control internal PUE as distinct from the cultivar's external PUE. This could then be used in conventional plant breeding systems using genetic marking to follow the trait into new breeding lines.

A8. SECTION A : Conclusions/Comment

In attempting to consolidate the complexity of the subject of PUE, I have formulated a simple table highlighting those traits in farming that we may increase or decrease with the aim of improving PUE. This list is not exhaustive and may require adapting to suit different farming systems, but the generality of the statements should cover the need for flexibility while providing the basis for better management principles.

Factors that should be INCREASED	Factors that should be DECREASED
The level of Soil Test P to above the critical level for a given farming system	Losses of P via runoff, erosion, or leaching
Increase P accumulation in the more readily available pools	Reduce the export of P in produce
Increase microbial and fungal activity	Reduce the uneven dispersal of wastes
Increase ability of plants to root well through management of soil structure.	Reduce accumulation in Low Availability Pools
Targeting and timing of correct P applications	Reduce the other nutritional constraints to crop yield potential
The use of various cultivars that have higher uptake efficiencies in rotation	Reduce the disease constraints to crop yield potential
Increase the amount of organic source P, and hence the organic P cycling	Impacts that have a detrimental affect soil structure
Using correct source of P depending upon specific requirement.	The use of single sources of P
Knowledge of actual P removed	

End of SECTION A

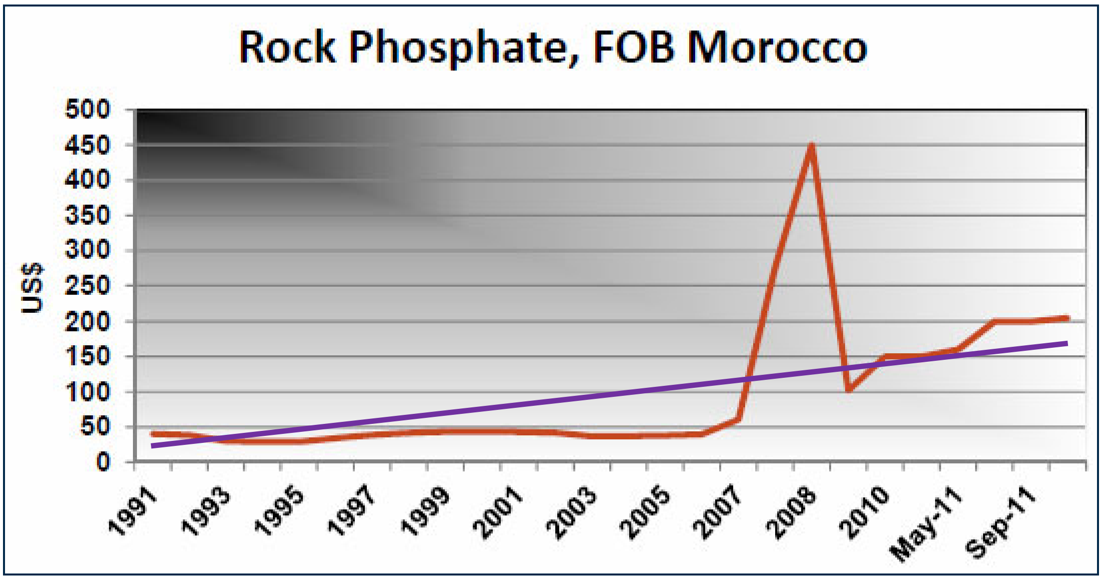
SECTION B :

The wider supply and recycling effects of Phosphorus

B1. Phosphorus supply

B1 (a) World reserves of rock phosphate (RP)

Some of the motivation for me in conducting this research project was derived from the background conversation regarding the looming scarcity of Phosphorus as a resource. Internet searches for detail on the subject only fuelled my concerns as many articles and postings highlighted the 'Peak Phosphorus' concept, a theory which would copy Hubbert's Peak Oil theory in 1949 (Wikipedia). The spike in Phosphorus prices in 2008, which saw the on-farm price of triple superphosphate in the UK rise from below £200 per tonne to nearly £800 per tonne within twelve months, was a game changer in many ways. The graph below shows the spike in price of Moroccan rock phosphate FOB; however my concern as a farmer is the purple trend line which ignores the spike. It is not the aim of this report to suggest prices of Phosphorus in the future, but the trend line shows a consistently increasing price.

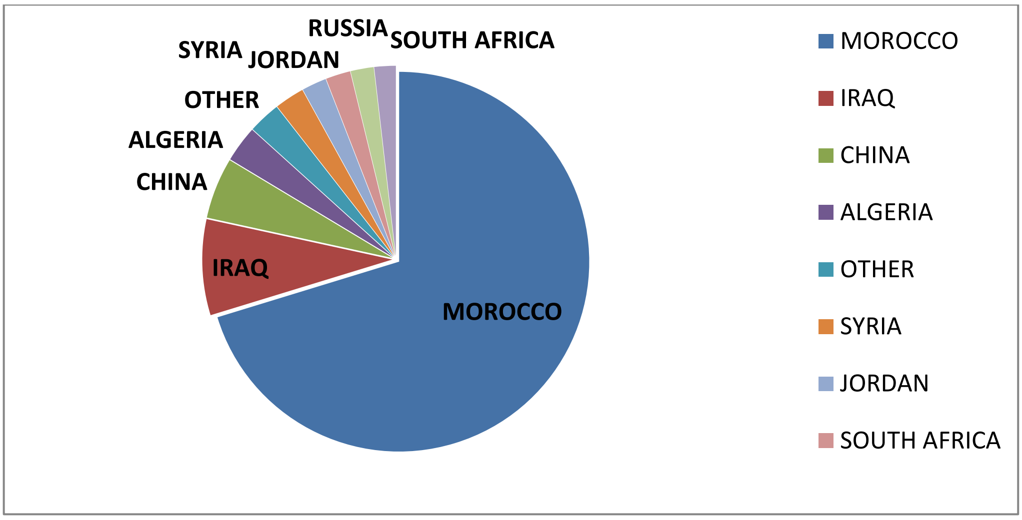


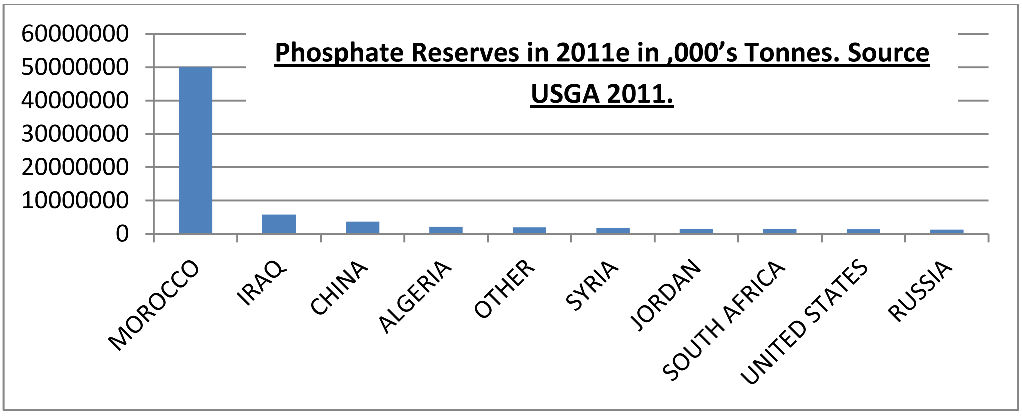
(Source: World Bank)

The fluctuation of commodity prices across the world makes it difficult for farmers to budget long term, and each decision of when to buy and sell has to be taken on the merits of the information supplied. With regards to Phosphorus supply, the numbers have changed in the past few years. The total reserve has been raised from 16 billion tonnes of Phosphorus in 2007 *(Ref USGA 2007)* to over 70 billion tonnes in 2011 *(USGA 2011).*

The factors that make these numbers more interesting are shown in the line graph and pie chart below:-

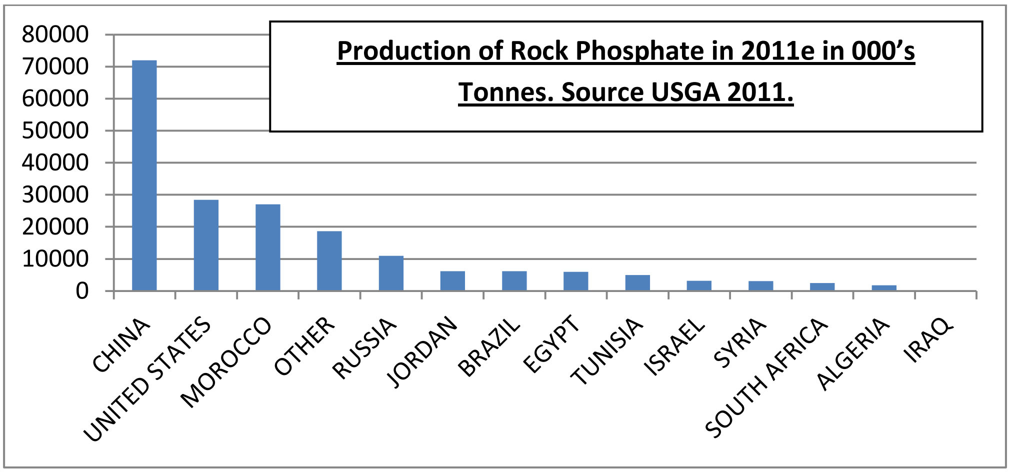
Phosphate Reserves in 2011[e] by %. Source USGA 2011.





These two graphs show the same data, just the graphical presentation is different. It is the fact that over 70% of the world's reserves are in two countries, Morocco & Western Sahara and China, and nearly 80% if you include a third, Iraq, which should be of concern.

The reserves have been listed, but these figures do not highlight the production concentrations, which are very different to the reserves figures, as shown on the next page:



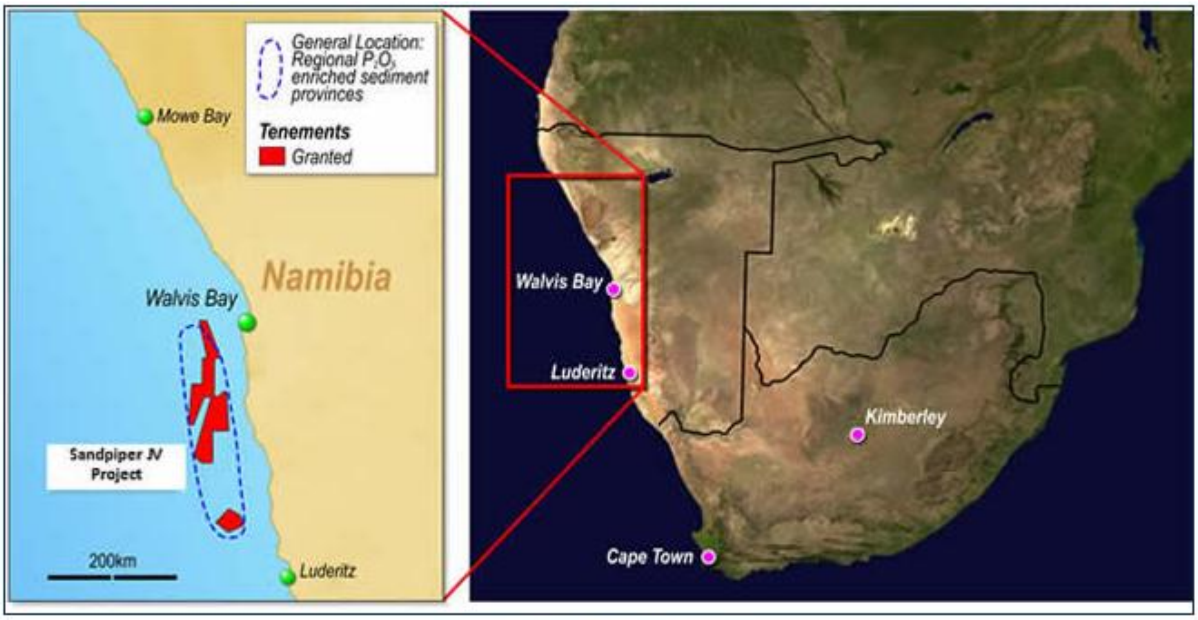
The first point to raise is that the yearly output figures vary greatly from the reserves data; from China being the largest producer with nearly 40% of the world's output in 2011, to the fact that Iraq, having the third largest reserve, produced none at all.

The issue that the UK should be aware of from a strategic point is: whether we are talking about production or reserves, supply is in the hands of the few. I am not suggesting for one moment that actions by any of these sovereign states would ever wish to destabilise a market in which they have so much influence, but rather the risk of the unforeseen. For instance, weather or geological catastrophes which could for a period halt supply/production from one of these main sources. The singular shock that may come to one of these sources would not have the same effect as if a major oil supplier was disrupted, because the time lag of supply restriction to food shortages would be measured probably in years rather than the weeks or months if it were to happen to oil, but the overall picture should be understood.

I am, however, strangely thankful for the 2008 price spike. The Morocco price graph above highlighted the FOB price for Phosphorus, which had remained under $50.00 per tonne for many years. At this level, and with the high grade and easy access to African-sourced Phosphorus, the resources to explore and mine new deposits were simply not economical.

With the post commodity price spike levelling at a higher FOB price, the economics of Phosphorus resource development changed. This has been illustrated in the case of an Australian company, 'Minemakers', which is in the process of developing deposits of Phosphorus found in North Central Australia, and off the coast of Namibia.

For illustrations see overleaf



Sandpiper Phosphate Project

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Further details of these developments can be found at http://www.minemakers.com.au/.

B1 (b) Consumption trends/time line. Will we run out?

As with many arguments when we talk about any resource use, the questions of 'will we run out?', and 'if so, when?', all depend upon your reference point of how far into the future you consider a long time. My five-year old daughter, after only experiencing her first term to date, cannot really comprehend the full 13 years that she will have to go to school. Our use in agriculture of mineral Phosphorus has developed over only the past 150 years or so, and known reserves stretch at projected consumption rates into the hundreds of years. We therefore have no immediate requirement to inflate the value of Phosphorus, to the detriment of food production on a global scale. The moral hazard in the early 21st century would be to restrict food production based upon trying to preserve P reserves.

There is, however, a need to recognise the importance of the nutrient on a longer term scale. Because Phosphorus, unlike oil, has no substitutes, it has been argued by Michael Mew 2011, that Phosphorus supply will not follow the bell-shaped curve as described by Hubbert. It is an argument with which I personally concur. No substitute is present, so as supply tightens, prices will rise. This will encourage more production (or capacity addition) and discourage demand. Phosphate rock prices will continue to rise until equilibrium is reached. Likewise an oversupply will cause prices to fall.

Because of the theory described, and the fact that global resources are unknown in quantity and quality, natural balances will be reached. Phosphate production will continue to rise, but may be at a decreasing speed to a maximum level, probably within 100 years. The production level will possibly reach 250-280 million tonnes per year, (against 191 million tonnes in 2011), and then instead of declining rapidly, will plateau for a period. This may coincide by the middle to end of this century with a levelling out in the world's population increase, and the slowing of growth of meat consumption.

This is all conjecture, and my personal feeling is that geopolitical issues regarding the distribution of Phosphorus will become limiting long before an actual and recognised shortage of the physical nutrient.

B1(c) UK consumption

It is worth covering the general picture for the UK, as there are some interesting and concerning trends developing which need addressing. The data shown is taken from *Defra's British Survey of Fertiliser Practice 2011*, and the *Agricultural Industries Confederation 2011*

Table 3: UK consumption of fertiliser nutrients ('000 tonnes)

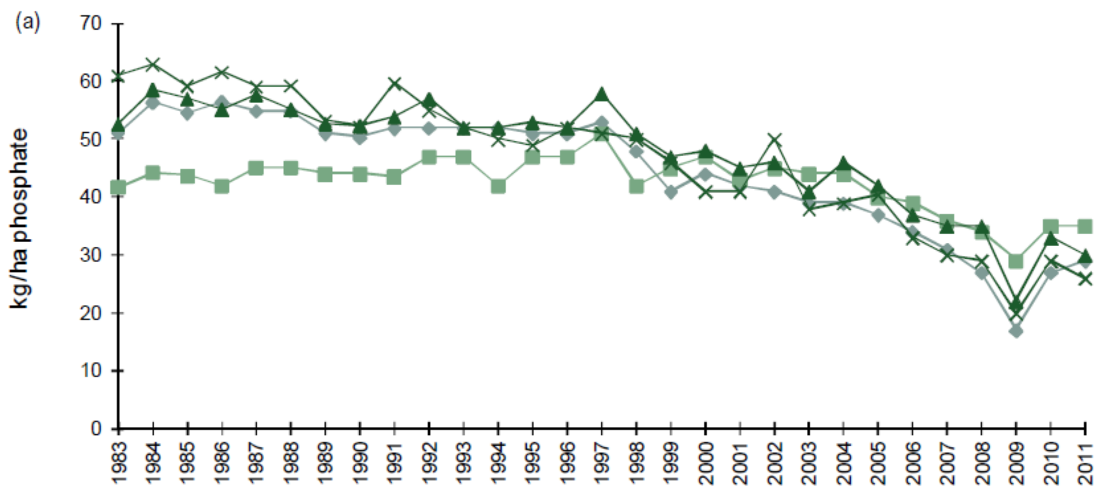
Growing season:	1999/00 10 yrs ago	2005/06	2006/07	2007/08	2008/09	**2009/10**	1 year % change 2008-09	10 year % change 1999-09
Nitrogen (N)	1268	1003	1008	1006	913	**1016**	+ 11.3	- 19.9
Phosphate (P_2O_5)	317	235	224	215	129	**184**	+ 42.6	- 42.0
Potash (K_2O)	409	325	317	325	208	**251**	+ 20.7	- 38.6
Total Plant Food	1994	1563	1549	1546	1250	**1451**	+ 16.1	- 27.2

Source: AIC Statistics

Total consumption rates for all the major nutrients have fallen on a UK basis over the past 10 years, with Phosphorus use having the greatest decline at 42%. What is also clearly seen from the table is the dramatic drop in use in the 2008/9 period, which coincided with the increase in on-farm prices for Phosphorus of over 400% from the previous year. The following year's use was back up again given the fall in Phosphorus prices, but the overall trend is still lower, and on a country-wide basis, the deficiency in 2008/9 has not been redressed.

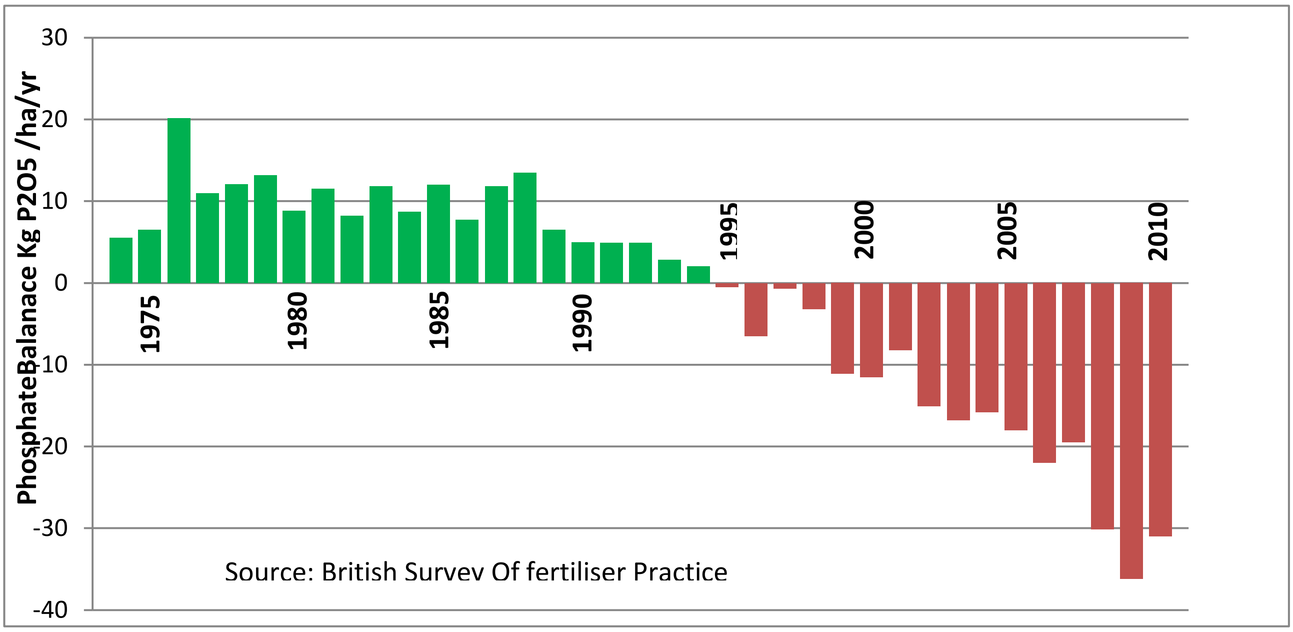
This information is corroborated from a different source when we consider average application rates.

Overall application rates (kg/ha) of (a) phosphate on sugar beet and potatoes
Great Britain 1983 – 2011



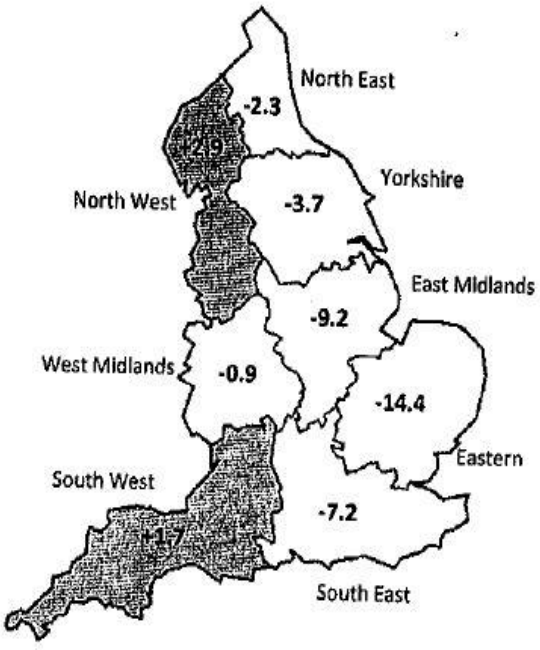
These data have more impact when we consider the offtake of Phosphate nutrition in arable crops in the UK over the past 35 years. The net yearly balance of Phosphorus inputs to outputs has resulted in an extended period of mining of the residual levels of Phosphorus in UK soils, as the graph below aptly illustrates.

Overall Annual Phosphate Balances in England and Wales for Cereals, Oilseeds, Potatoes, and Sugarbeet,(excluding manure inputs).



B1 (d) Other sources of Phosphorus in the UK

The above graph is slightly misleading as it does not take into account the use of animal manures which are available and used to a certain extent. An excellent paper, recently published in 2011 by *Bateman et al,* specifically looked at the Phosphorus available in animal wastes across England. This was then compared against outputs on a regional basis to show the surplus or deficit of the Phosphorus in wastes against the requirement by crops grown in that region. The map showing the regional figures is shown overleaf.



Phosphorus surpluses and deficits on a regional scale. Units are 1000 tonnes of Phosphorus. The shaded regions have a surplus in Phosphorus. The total available for export from the West is 4.7 thousand tonnes.

The total Phosphorus content of housed animals in England is 80,700 tonnes, or the equivalent of over 400,000 tonnes of triple superphosphate, TSP. On a countrywide scale, this could satisfy over 70% of the requirement for Phosphorus across England. This however is simply not only uneconomical but impractical. The total figure for animal waste in England alone is over 50 million tonnes. This is largely applied to land near to the point of source because the cost of transport is too great for the value of the Phosphorus (and other nutritional benefits added together) that may be recovered.

B1 (e) Comment on Phosphorus Supply

There is clearly a disconnect between the livestock producing sector of agriculture and the arable sector with regard to closing the Phosphorus loop. The relatively low concentration of Phosphorus per tonne of waste presents a significant problem given the cost of transporting bulky waste long distances. The ability to concentrate the level of nutrients in the waste before transport, or moving the waste-producing animals into regions of overall Phosphorus deficit should be considered as longer term solutions to Phosphorus recycling and perhaps sustainable waste management.

This process of surplus Phosphorus in animal wastes becoming separated from arable land that has a Phosphorus requirement is apparent all across the globe and at different scales.

B2. Global Phosphorus production and use

Between 1992 and 2011, global production of phosphate rock rose by an overall 35%, reaching a record level of 194 million metric tonnes (Mt) in 2011. This equates to an average annual growth rate of 1.8% during that period.

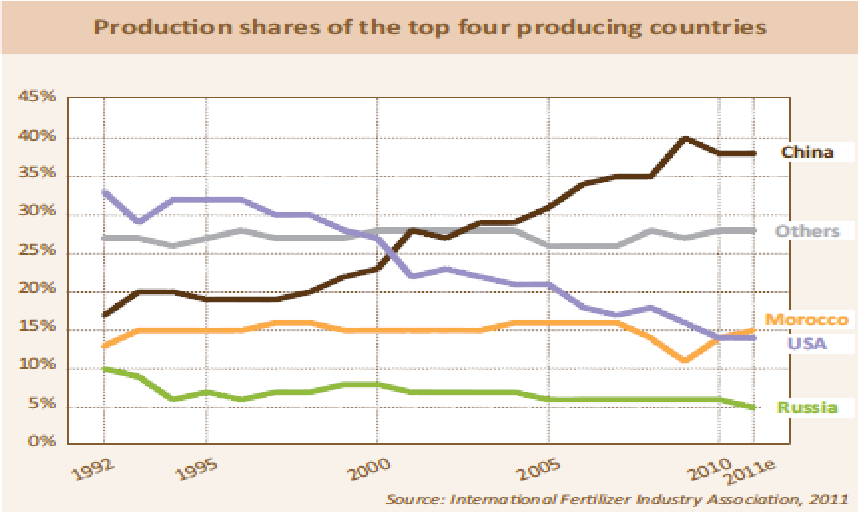
Much of the net increase in production has been driven by rising home deliveries in producing countries. While the global trade of phosphate rock remained relatively stable at around 30 Mt from 1992 to 2010, home deliveries increased by 52 Mt to reach 164 Mt in 2011. The share of home deliveries in total sales grew from 77% in 1992 to 85% in 2011. For reference, 'Phosphate concentrates' refers to commercially traded and consumed phosphate rock that has been processed to higher grades. 'Phosphate ore' would grade between 5% and 39% P2O5, while phosphate concentrates would grade between 28% and 40% P2O5.

Phosphate ore is currently mined from igneous and sedimentary deposits. Production from sedimentary deposits accounts for 85% of world output, the remaining 15% coming from igneous deposits. However, sedimentary deposits account for about 90% of the world's known phosphate reserves. Phosphate deposits of igneous origin are currently being exploited in Russia, China, Brazil, South Africa, Canada, Finland, and Zimbabwe, in order of declining production. The main countries where sedimentary phosphate deposits are exploited are China, Morocco, the United States, Tunisia, Jordan, Syria, Israel, Egypt, Peru, Viet Nam, Australia and India. Guano-derived phosphate deposits are mined in only a few countries, such as Australia (The Territory of Christmas Island) and Nauru.

B2 (a) The Big 4 Producers

From 1992 to 2011 production of phosphate rock in these four countries showed quite divergent paths. China became the world's largest producer, with a market share that expanded from 16% in 1992 to 35% in 2011.

See chart on next page



The United States lost its prominence in the early 2000s, while the market shares of Morocco and Russia have remained relatively stable. Production in all the other countries as a whole increased, accounting for a stable 28% share of global output. Emerging production in Egypt, Algeria, Australia, Syria and Peru has offset the gradual decline in formerly large phosphate rock producing countries, such as Kazakhstan, Togo, Senegal and Nauru.

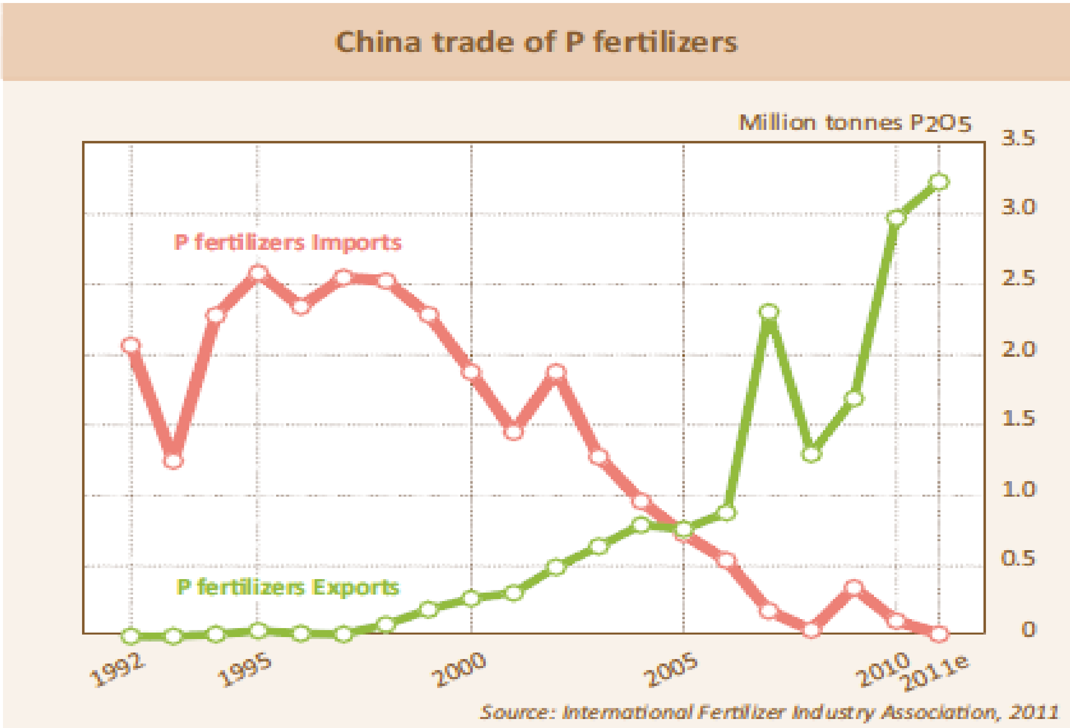
Morocco accounted for only about 14% of global phosphate rock production in 2011. In terms of geographical distribution, close to 16 countries are producing phosphate rock in Africa and West Asia; 10 countries in East Asia and South Asia and Oceania; 7 countries in the Americas; and 4 countries in Europe and Central Asia.

USA Between 1992 and 2011, production of phosphate rock in the United States registered a gradual decline of close to 2% per annum. Rock production dropped from 47 Mt in 1992 to 27 Mt in 2011 due to four factors: a reduction of exports of processed phosphates because of rising domestic supply in large importing countries such as China; a decline in the production of other Phosphorus based products; the termination of US phosphate rock exports in 1999/2000; and tightening environmental regulations on mining.

Russia Between 1988 and 1994, production of phosphate rock in Russia fell three-fold due to the collapse of its domestic fertiliser consumption. Russia's exports of phosphate rock peaked in 1998 at close to 5 Mt and have gradually declined to less than 1.5 Mt since then. However, during the past decade rock production in Russia has remained stable at around 10-11 Mt as home deliveries have gradually recovered.

The Chinese influence. China has registered a sustained expansion of production of phosphate concentrates, notably since the mid-1990s. IFA estimated phosphate production in China at close to 75 Mt in 2011, representing three-fold growth compared with 1992. This expansion has been driven by a national investment policy encouraging domestic production of phosphate fertilisers and the reduction of China's prevalent heavy import reliance. Home deliveries of phosphate concentrates have shown sustained expansion during the past 20 years. Meanwhile, owing to the implementation of export restrictions on raw materials in order to increase the lifespan of this resource, China's exports of phosphate concentrates reached a peak of 5 Mt in 2001 and gradually decreased to less than 0.8 Mt in 2011.

Rock concentrates are used mostly to produce P fertilisers. Earlier, growth in P fertiliser output was driven by the need to meet China's growing domestic demand. This demand resulted in a massive reduction of imports. Much of the increase in China's Phosphorus fertiliser production in recent years has been earmarked for export.



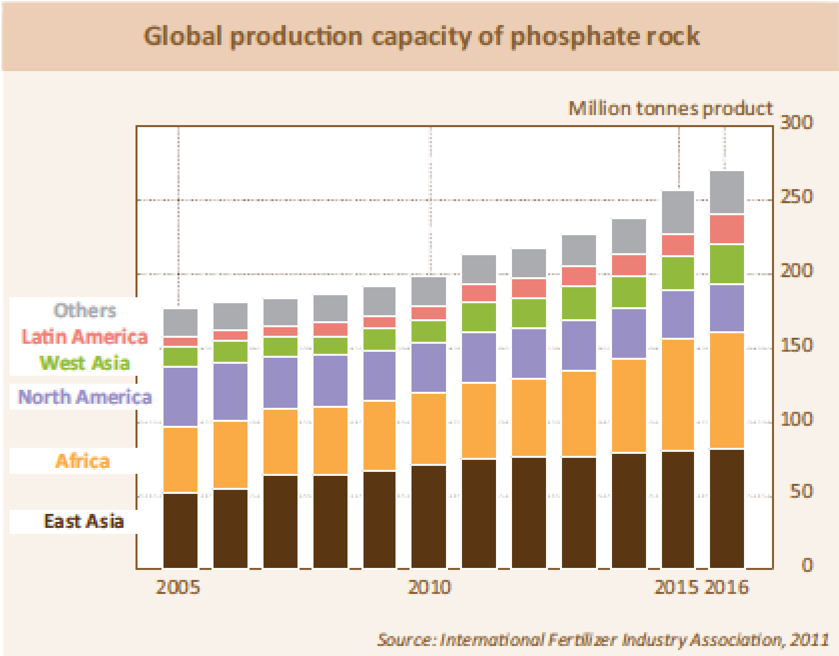
B2 (b) Phosphate capacity now and in the future

Based on the 2011 IFA survey of future phosphate rock supply, world phosphate rock capacity is projected to increase by an overall 26% (from 203 Mt in 2010 to 256 Mt in 2015). Rock potential supply is projected to increase in virtually all regions, but the largest increment would occur in Africa, accounting for half the growth between 2010 and 2015. Other regions that would see an increase in capacity above 5 Mt include Latin America, West Asia, East Asia, and possibly Oceania. Productive capacity is projected to decline in

North America. China would contribute 10% of the world capacity increment between 2010 and 2015, compared with nearly 95% between 1990 and 2000.

On a global basis, all these developments have the potential to add close to 53 Mt of productive capacity between 2010 and 2015. The largest increases would occur in 2011 and 2015. Expansions from current producers would account for two-thirds of the total capacity increment during the forecast period. The remaining 19 Mt would come from new exporters and new integrated operations.

Over the next five years, new export-oriented capacity is likely to emerge in Peru, Australia, Kazakhstan, Namibia and Senegal. Additional capacity is projected to come on stream in established exporting countries with sizeable expansion plans; these would include Morocco, Algeria, Togo, Syria and Vietnam.



B2 (c) World resources:

The data discussed so far refer to **Reserves,** which can be defined as:-

> The part of an identified resource that meets the minimum criteria related to current mining and production practices including grade, quality, thickness, and depth. This can be economically extracted or produced at the time of the determination. This may be termed marginal, inferred or inferred marginal reserves. This does not signify that the extraction facilities are in place or functional.

Resources are those concentrations of naturally occurring phosphate material in such form or amount that extraction of a product is currently or potentially feasible. Resources are divided into many categories depending upon the amount of pertinent information available and if it is economic, marginally economic or sub-economic to exploit these resources.

There are recognised deposits elsewhere in the world which do not make up the reserve figures as they are either not accessible using present recovery methods, or are highly uneconomical to access. Examples of such would be the resources that are known to lie in western Florida, but which have the city and surrounding developments of Tampa Bay sat directly above them, and could not be accessed without the wholesale removal of the city. Phosphate rock resources occur principally as sedimentary marine phosphorites. The largest sedimentary deposits are found in northern Africa, China, the Middle East, and the United States. Significant igneous occurrences are found in Brazil, Canada, Finland, Russia, and South Africa. Large phosphate resources have been identified on the continental shelves and on seamounts in the Atlantic Ocean and the Pacific Ocean. World resources of phosphate rock are more than 300 billion tons.

B2 (d) Comment on global Phosphorus production and use

Phosphate rock production has steadily increased over the past 20 years, contradicting some assessments of declining output. While the concentration of production has raised some concern, which has been expressed in public debates, the number of producing countries actually expanded from 28 in 1992 to 37 in 2011.

As a result in the increase in the FOB price of rock phosphate, a number of sites not considered fit for mining previously are now being investigated or developed. If all these projects with known exploitable reserves proceed as planned, there will be enough phosphate rock concentrates to meet demand during the next five years.

The recognition of the strategic importance and monetary value of reserves is being exploited across the globe. This is also being supplemented by the investment in to the downstream processes systems to value-add to the raw commodity.

As a UK farmer, I am not considering the ‘lack of reserve’ as a near or medium term threat to food production in the UK. The value in the commodity however, I can see remaining reasonably stable, subject to specific geopolitical shocks, but with a general increase in value as production and transportation costs increase.

B3. Phosphate recovery from wastes

Whether the supplies of mineable phosphate minerals are subject to being depleted in 250 years or 1000 years is somewhat academic in today's world. The requirement to maintain the quality of fresh and coastal waters will ensure that systems will need to be developed to capture certain streams of Phosphorus which would otherwise cause serious detrimental environmental effects. Much of the work in this field has been to reduce the impact that waste water systems have had on waterways and the seas into which they have been historically discharged.

The extraction of Phosphorus from wastewater streams in Europe comes from the legislation controlling disposal. The wastewater industry has to dispose of the treated liquid fraction it processed, and typically releases this into watercourses. The present limits, which vary according to certain grouping of member states, are based upon a concentration of permits on a kg of P/head/year for each state *(Dawson 2011).* For the UK, this level is set at 0.36kg P/head/year. This is approximately 40% higher than the recommended amount of the annual intake of P/head/Year.

B3 (a) Ostara -the first commercial Phosphorus recovery system from water waste streams

This company began life in 2005 in Vancouver in Canada having taken on the technology originally developed at the University of British Columbia by the team led by Don Mavinic and Victor Lo, with whom I met on my travels.

A product called Struvite, which is magnesium ammonium phosphate ($MgNH_4PO_4$) has been found in many sewage systems across the developed world as it has a tendency to form spontaneously and in an uncontrolled manner within pipework systems. This then reduces the flows and even blocks pipe networks with the result that they have to be dug up and replaced. A system was developed and commercialised by Ostara with the first plant being built in Durham, Oregon in the North Western USA. The system processes over 400,000 litres per day and is successful in delivering a 95% orthophosphate removal from the given waste stream and produces as a result over 500 tonnes per year of Struvite which is marketed under the brand name Crystal Green^{R}

The flow diagram of the process is shown in the Appendix at the end of this report.

B3 (b) Ostara in the UK

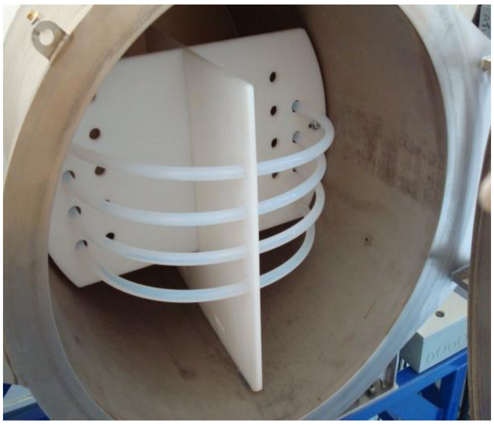
In partnership with Thames Water, Ostara have built a similar facility to the one in Oregon at Thames Water's Slough Sewage treatment plant in London. This will be the first large scale plant of its kind in the UK, and the production of Crystal Green[R] will also be marketed accordingly. The total production of fertiliser from this system is expected to be in the region of 150 tonnes per year, and it will no doubt be marketed as a premium Phosphorus source into specific markets. The small quantity produced compared to the UK's use of mineral Phosphorus fertilisers will mean it will not make any impact on the wider fertiliser supply market.

B4. Case Study:- Improving the recovery of Phosphorus from dairy slurry

DERC, University of British Columbia.

During November of 2011, I was invited to visit the University of British Columbia's Dairy Research station in Agassis in Western Canada. This university was involved with the original development of the 'Ostara' system to extract Struvite from wastewater treatment plants on an industrial scale.

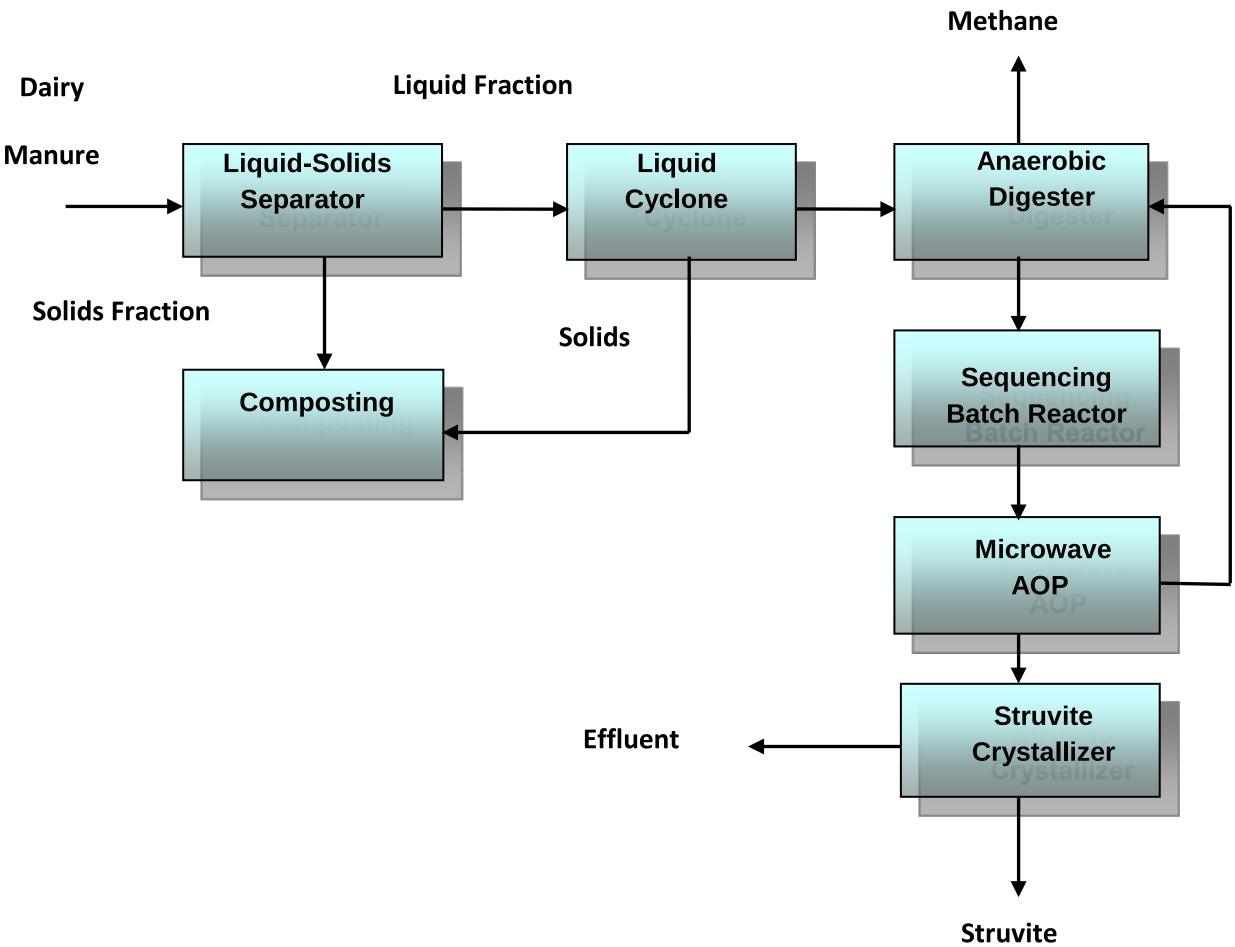
The system shown and described below is an experimental trial to try to increase the recovery of Phosphorus as Struvite from dairy waste. The unique part of this process is the use of microwaves to 'attack' the slurry before entering the Struvite extraction process, such that more of the complex Phosphorus is released.



The manure passes through the white piping as shown. The stainless steel container is the 'microwave cooker'. The large standing machine to the right of the 'cooker' is the microwave generator.

Crystallising Tower **Struvite Pellets**

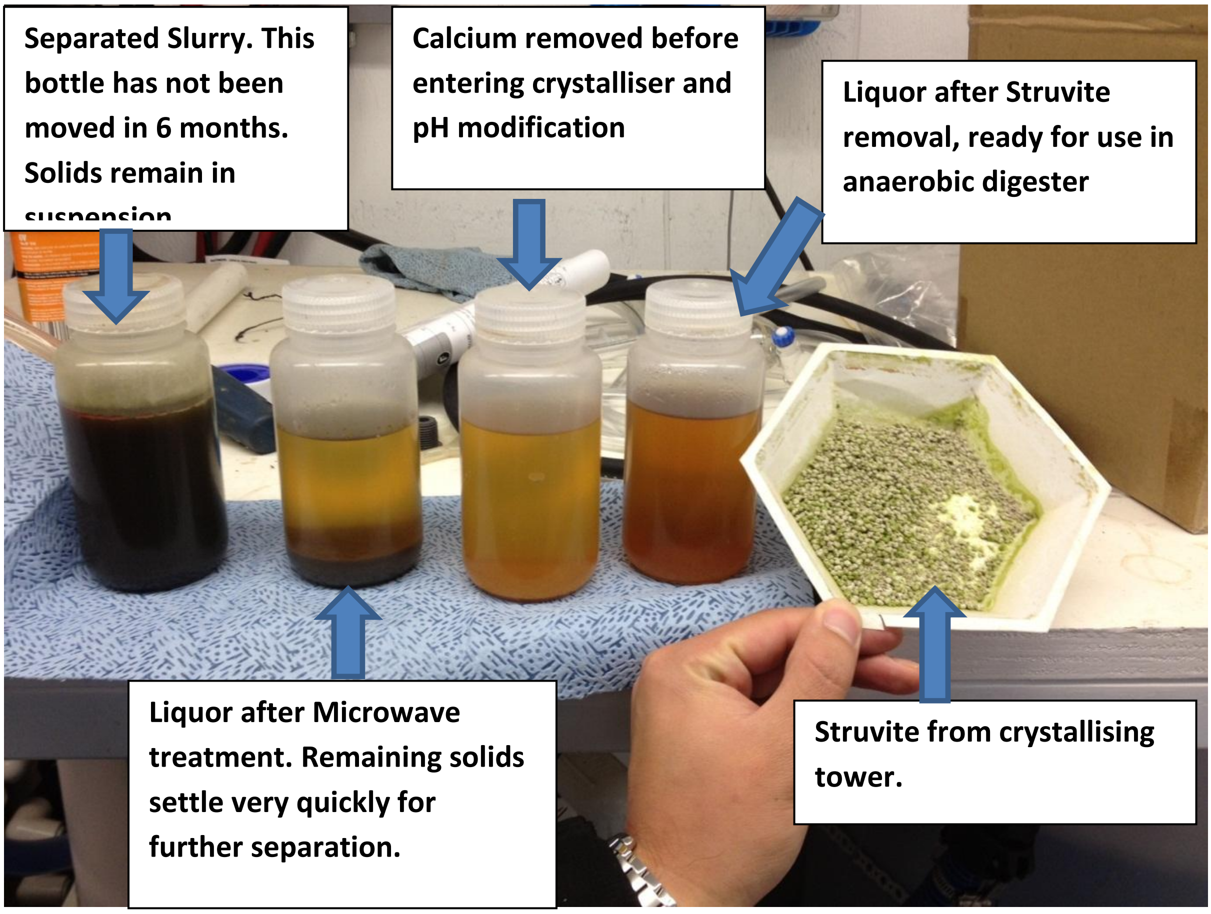
Below : A generalised flow diagram for dairy slurry separation



The effect of microwaving the slurry is to breakdown the long chain carbon molecules which bind the Phosphorus more strongly.

Prior to microwaving, there is approximately 130 ppm of P, 50 ppm of which is soluble; the remaining 80 ppm is bound. Following the microwaving process this changes to approx. 125 ppm of soluble Phosphorus, leaving only 5 ppm bound.

The positive side effect of this process, besides increasing the recovery of phosphate, is that the remaining liquor is far more efficient once added to an anaerobic digester, where total time within the digester reduces from approximately 20-25 days to 5 days. This means that a digester only 20% of the current size would meet the output of the dairy.



The specification for the process is, for commercial and technical reasons, not listed in this document; however, some output numbers have been roughly calculated to show the limiting factors:-

> Based upon a 20-head dairy cow production unit on slatted floor housing with slurry collected, the above process using the microwave technology will produce approximately 175 grams of Struvite per day.

B4 (a) Comment on the Struvite process

This is clearly a very small amount of useable/saleable Struvite, and even scaled up to commercial dairy herds, the economics of recovering Phosphorus in this manner are still not feasible. The specific area where I see this system being used is in combination with bio-digesters on a large dairy herd scale. The high energy requirement during the microwave process may be offset enough during the energy capture from the improved and faster digestion of the microwaved liquor. This process is clearly at the beginning of its development phase, and this particular university has a proven track record in taking ideas through to the commercial world.

B5. Recovery of Phosphorus from sewage sludge and sewage sludge ashes with the thermo-reductive process

This system is being undertaken by Thermphos International in the Netherlands. The company produces many types of high quality phosphate products that are generally used in industrial applications and products, its usual source for Phosphorus being imported rock phosphate. It has aimed to replace 40,000 tonnes per year of their P_2O_5 intake (17.5 kt P) by recovered materials, of which sewage sludge ashes produced from around Europe are being used. Today, the P-content in the European sewage sludge could currently replace roughly 15% of the phosphate imports to the EU. For many years systems have tried to recover Phosphorus from sewage, sludge and ashes alone in various ways of which none has yet been realised at industrial scale. The reason for this failure lies firstly in the wet chemical approach, requiring complex and small efficient processes, often by means of liquids hard to handle; and secondly in the use of liquid or dewatered sludge as well as waste water, which results in a further decrease in efficiency mostly because of high mass flow and matrix effects. The addition of a proportion into Thermphos' inputs has allowed at least a certain recovery of the Phosphorus.

Phosphate content

The typical P_2O_5 content of phosphate rock is 30-40% (= 13-17.5% P). The phosphate content of waste streams is usually lower. The phosphate (amongst other constituents) is reduced on an inductively heated coke bed to white Phosphorus, which can either be condensed to recover white Phosphorus, or, after combustion of the off-gas, retrieved as phosphoric acid. Further products can be an iron alloy as well as a heavy metal mixture (both usable in the steel industry) as well as a silicate slag for the use in cement ovens and occasionally a high calorific gas (mainly carbon monoxide). If the remainder is made up of inorganic compounds, this will lead to more slag per tonne of P_4. This will affect the energy efficiency of the process negatively. The heat in slag is lost since it requires a special cooling process in order to make it suitable for civil engineering purposes. The slag takes up a substantial amount, about one-third, of the total electricity consumption of the process; therefore extra slag should be avoided if possible.

See next page for Comment on the thermo reductive process

B5 (a) Comment on the thermo reductive process

Being able to have systems available to extract Phosphorus from the residues of burnt sewage sludge is clearly beneficial to burying the remaining ash. A pure and valuable product is produced, and reduces the requirement for mined Phosphorus. The overall process of burning sewage sludge is I believe highly wasteful in terms of energy compared to the value that treated sludges could add directly to soils. The issues of returning sewage to land and the issues of heavy metals will for now continue to rage, and it is not the remit of this report to delve in to those issues.

End of SECTION B

5. Politics

As with seemingly anything to do with agriculture in the 21st Century, politics always has an impact on factors that will affect us in the future. The longer term aspects of this study required that the general subject of politics was considered. So I made relevant enquiries at a national level and was fortunate to book a meeting with the Agriculture Minister for the UK, Jim Paice MP, during early March 2012. As a result of my original contact with the minister, an internal DEFRA briefing was produced on Phosphorus covering all the relevant issues for him. A summary of the briefing's findings are covered below:-

- **Phosphorus resource security:**

DEFRA is aware of the newly revised USGA estimates of Phosphorus reserves across the world, and that over 75% of these resources are in the single region of Morocco and Western Sahara. The concerns therefore over 'peak phosphorus' are not at a level where a strategic position needs to be made to secure the resource.

However, it makes economic sense to minimise our dependence on imports from other countries, especially for an essential, but limited resource for which there is an increasing world demand.

British agriculture should maintain a focus on improving resource efficiency, and 'closing the loop' by recovering and re-using Phosphorus sources. This reduces dependence on imports and creates a national 'secondary supply' of the resource.

This drive should therefore reduce expose to supply difficulties and increased price fluctuations.

The EC is in the process of publishing a green paper, due later in 2012, on the sustainable use of Phosphorus.

- **Environmental pollution**

There is a widespread failure across the UK to meet the Water Framework Directive (WFD) with regard to Phosphorus in rivers and lakes, particularly in England. 33% of the rivers in England and Wales that fail to reach 'Good Ecological Status' under WFD do so because of Phosphorus loading.

The impact of agriculture on the levels of Phosphorus according to CSF and ADAS modelling suggests that on-farm measures can deliver up to a 40% reduction in Phosphorus loading.

The countryside survey has shown a significant reduction in plant-available Phosphorus in the soils across all habitats in England between 1998 and 2007. This includes an 8% reduction on arable land, and over 20% on grassland, which has largely been driven by the reduction in Phosphorus fertilisation and the reduction of livestock numbers.

90 million tonnes of organic manures are produced per annum across the UK, increasing to 100 million tonnes where sewage sludges, composts and other organic materials are included. The correct use of the manures is important to ensure that they are employed in a beneficial manner and not one that may increase the possibility of detrimental environmental impact.

The 'water quality benefits of UK inland and coastal wetlands may be as high as £1.5 billion per annum, with planned river quality improvements possibly generating values up to £1.1 billion per annum. Additionally, wetlands are very valuable for other reasons, for example recreation and tourism, according to the UK National Ecosystem Assessment (NEA).

- **DEFRA Support for Farmers**

The aim of DEFRA with regard to Phosphorus is to include it within its drive to make overall nutrient management decisions better.

This is done through current and continually updated advice via comprehensive guidance as available via the Fertiliser Manual (RB209), and the Code Of Good Agricultural Practice. Also decision support tools, such as MANNER and PLANET. This advice is delivered through the Farming Advice Service.

The advice within RB209 focusses on achieving and maintaining index 2 for soil Phosphorus.

- **Evidence and Research Interests**

Further work studying Environment Agency data sets, standards and understanding of eutrophication and modelling tools are evolving and evidence gaps are being reduced by local investigations. DEFRA is working on analysis of the damage costs of eutrophication, the cost/benefit of future control options, and the extent of future influences, e.g climate change.

For diffuse nutrient pollution, learning from on-going pilot and research studies will influence DEFRA's future approach. For example:-

- Demonstration Test Catchments
- Water Framework Directive pilot catchments programme
- On-going review of Catchment Sensitive Farming.
- Natural Environment Research Council's £9.5m macronutrients research programme.

5 (a) Comment on the political scene

My personal interpretation of the briefing document, and from discussions with the minister, suggest that the strategic uses of the resource are simply not factors impacting department strategy, in either a short, medium or long term nature.

The efforts with regard to Phosphorus are to reduce its environmental impact across all land types and cropping systems with regard to water quality under the WFD. This ultimately is being driven from regulations that are being decreed at an EU level. The formulation of these directives from the EU is to meet public health and environmental targets, and is not based upon the need to meet our food security needs at an EU or national level.

The UK's response to Phosphorus management will be based around an overall nutrient management policy for farmers.

The basis of the RB209 data will continue to be used by the relevant bodies in applying regulations. If British agriculture wants to work outside RB209, then work needs to be done to make the document more relevant to different farming systems. There is a danger here, however, that the production of a more refined advisory system for Phosphorus applications, may be used to restrict the broad approach available to farmers in the UK today.

6. The next step?

With regard to my enthusiasm to see that the RB209 recommendations are improved in a manner which allows farmers to make better informed decisions for Phosphorus applications, I have hit many issues. One of the main restrictions on formulating a revised recommendation is the access to relevant and up to date data. The Phosphorus recommendation systems that are more accurate and which are used in differing parts of the world have an accuracy based upon research which has been carried out on a national/regional basis, where the correlations prove significantly accurate to offer more targeted application amounts of Phosphorus. These data sets do not transpose into a UK system with enough accuracy to be used here, so new data needs to be gathered with the prospect of showing a statistically significant variance.

One of my first meetings during my research was with Prof. Phil White from the James Hutton Institute in Dundee. Prof. White was involved with editing the Phosphorus recommendations that are published in the latest version (8^{th}) of the guidance. This meeting gave me the opportunity to understand the reasoning behind the formulation of the figures which have proved robust under UK conditions and extensive peer review. However, my thoughts that the system could be improved have led me full circle back to Dundee and further discussions and a meeting with Prof. White and Dr Tim George. The outcome of these discussions is to conduct a formal study across UK arable systems, using this Nuffield Arden research project to kick-start the data collection process.

I am therefore looking to involve as many arable farmers across as wide a range of soil types and arable farming systems as possible who would be keen to take part in a Hutton Institute managed project. The requirements for this are as follows:-

- To be a UK arable farmer growing cereals/oilseeds on historic cereal/oilseed land.
- The ability to record yield data from combine in-field yield monitoring technology.
- To take field samples (two each year) between designated dates and following a sampling protocol.
- To stay in the programme for three years
- To designate approximately one acre for this study, and farm it in the same manner as the rest of the field except with possible differing Phosphorus input levels.

We are looking to compile yield data against a number of soil factors *as listed on next page* and then to change the Phosphorus recommendations in year two, record yield data and soil test and monitor the differences to see if any factors can be identified which may allow us to modify the Phosphorus recommendations for the future:

- Total P
- Olsen P
- OM
- Clay content
- CEC
- Ca
- Fe/Al
- pH

This complex soil test in year one should allow us to correlate the yield figures against Phosphorus levels and other soil factors with the aim of showing with greater accuracy the link with Phosphorus use and soil characteristics in a UK arable system.

6 (a) Schematic of trial process

May 2012	Identify test sites- volunteer farmers	
May 2012	Start-up meeting of advisory committee to agree protocols	
July/August 2012	Measure yield of crop within the sites	
August 2012	Comprehensive soil sample sent to lab	
August/September 2012	Lab results obtained, data to JHI, collated+analysed	
August/September 2012	Apply/Not, P as per normal system across all site	
December 2012	Show broad results from first data set and formulate alternative P application regime for 2013 via meeting of advisory committee	
January	Communication with all farmers and project partners	
July August 2013	Measure yield of crop within the sites	
August 2013	Soil sample as per instruction.	
August 2013	Split each site in to two applying P as per normal system across 50%, and applying a revised P as decided by Hutton Institute	
August/September 2013	Lab results obtained, data to JHI, collated+analysed	
December 2013	Meeting of advisory group, show end of Y1 results.	
July/August 2014	Measure yield of crop within the sites this time as 2 separate areas.	
August 2014	Soil sample as per instruction on each part of site	
August/September	Lab results obtained, data to JHI, collated+analysed	
By December 2014	Meeting of advisory group, decide further actions	
January 2015	Publication of data.	

6 (b) The catch?

As in any process there are efforts to be made. This wide range experiment is rarely carried out because of the need to follow a protocol and the time and costs that are incurred.

The costs:- Soil samples, a total of one comprehensive, and three more basic tests.

The time:- Management to mark out one acre plot each year for three crops, over two years. To be able to record the specific yield from combine technology over the specific site in Year 0, Year 1 and as a split site in Year 3. To take soil tests as per prescribed protocol during a specific window of time, post three harvests. To apply Phosphorus to half the split site in Year 2 as prescribed by the Hutton Institute.

6 (c) What's in it for you, the farmer?

The lack of data for researchers is a constant battle. The costs of taking large scale soil samples, in monetary terms, time and scale of labour, results in projects like this being rarely carried out. This project could genuinely provide the data for the following:-

- A confirmation that the RB209 figures have to date been the basis of good agricultural practice.
- The ability to recognise those factors that can be used to give more accurate Phosphorus recommendations.
- The ability to prove with data to regulatory bodies that the industry is following best practice, and to reduce the impact of bad regulation.
- Economics: we can save inputs where they are not needed, and improve crop potential by adding to those areas that are required to maximise yield.
- Environmental: better Phosphorus management will reduce the opportunity for P to have an adverse environmental impact.
- The opportunity to be part of the system that improves the system!

C7. Closing Remarks

This Nuffield Arden Study has been a journey in every sense. My regrets are that I could not visit and consider those tangents which a dynamic research project like this teases you with. I have valued every moment, and the time that this project has given me to think in a different way to my normal life has been invaluable to me personally in the realms of this project, my business and my home life.

Thanks again for all those who have given their time and who have supported me.

Nik

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8. Glossary/Abbreviations/Conversions

DAP	Di-ammonium phosphate
K	Potassium
MAP	Mono-ammonium phosphate
Mt	million metric tonnes
N	Nitrogen
P	Phosphorus
Struvite	Magnesium ammonium phosphate ($NH_4MgPO_4 \cdot 6H_2O$)
t	metric tonne (= 1000 kg)
Adsorption	The sorption of a mineral on to the surface of a solid structure.
Absorption	The sorption of a mineral within the structure of a material.
Desorption	The opposite of adsorption and absorption, i.e. the release from soil.
Mineralisation	The process whereby organic Phosphorus is broken down into orthophosphate for absorption by plants.
Phosphate	PO_4^{3-}
RP	Rock Phosphate
PUE	Phosphorus Use Efficiency
Orthophosphate	$H_2PO_4^-$
Genotype	The genetic make-up of an organism
Phenotype	The composite of an organisms characteristics or traits
Cultivar	A particular plant selected for desirable characteristics

Units & Conversions

P	$= 0.44*P_2O_5$
P_2O_5	$= 2.29*P$
Mt	$= 10^9$ kg

Material	Phosphorus content (%P by weight)
Commercial fertilisers:	
phosphate rock	8.5 - 13
phosphoric acid	43.64
MAP	22.69
DAP	20.08
TSP	20.08
SSP	6.55
NP	6.6 - 10.9
NPK	2.2 - 10.9
Organic P fertilizer	10.91
Organic NP fertiliser	5.24
Other material:	
Human urine	0.02-0.07
Human faeces	0.52
Human excreta	0.35
Activated sewage sludge	1.4
Sludge (from biogas digester)	0.48 - 0.77
Struvite	13 - 14
Cow dung	0.04
Poultry manure	1.27
FYM (Farm Yard Manure)	0.07-0.88
Rural organic matter	0.09
Vermicompost	0.65

Crop residues	0.04 - 0.33
Urban composted material	0.44
Oil cake (by-product from oilseed processing)	0.39 - 1.27
Meatmeal	1.09
Bonemeal	8.73-10.91

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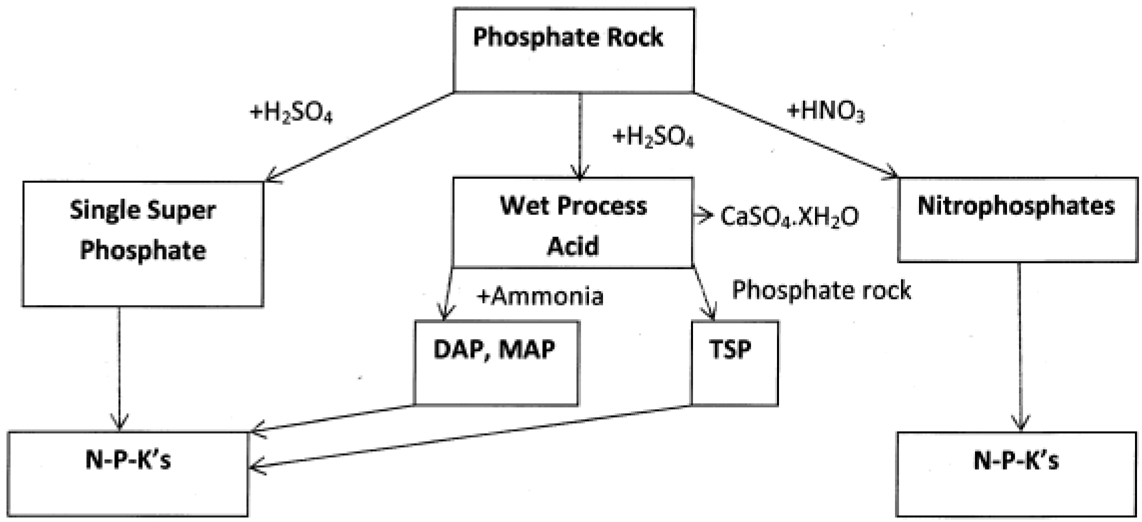
10. Appendix

10a Flow diagram of Phosphate fertiliser production from Phosphate rock.



10b The Flow Diagram of the Ostara Process