Nuffield Farming Scholarships Trust
The Frank Arden Award 2011

Sponsored by The Frank Arden Trust, The Crown Estates and Yara UK Ltd.

"Fertilisers for the Future"

A Nitrogen Perspective

Mark Tucker

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 Mark Tucker’s report and researches the technical position vis a vis Nitrogen. It was not his intention to visit other farmers but to investigate the highest levels of scientific research.

Nik Johnson concentrated his study on Phosphorus and has written a separate report.

Disclaimer

This publication has been prepared in good faith on the basis of information available at the date of publication without any independent verification. The Nuffield Farming Scholarships Trust does not guarantee or warrant the accuracy, reliability, completeness of currency of the information in this publication nor its usefulness in achieving any purpose.
Readers are responsible for assessing the relevance and accuracy of the content of this publication. The NFST will not be liable for any loss, damage, cost or expense incurred or arising by reason of any person using or relying on the information in this publication.
Products may be identified by proprietary or trade names to help readers identify particular types of products but this is not, and is not intended to be, an endorsement or recommendation of any product or manufacturer referred to. Other products may perform as well or better than those specifically referred to.

Abstract

Manufactured nitrogen fertiliser has become a staple input in modern, intensive agricultural systems. Approximately half of the world's food production can be directly attributed to the use of it *(Erisman 2008),* thus making it an essential input if agriculture is to support demands for both feeding and fuelling the world. First manufactured over 100 years ago, approximately 150m tonnes per annum of nitrogen is now consumed by agriculture. This is approximately the same amount of nitrogen that is fixed through natural biological processes and lightning. Effectively the loading of reactive nitrogen into the environment has doubled as agriculture has attempted to support the growing population.

With such a loading into the global nitrogen cycle come the challenges of the consequential environmental impact. This impact is due to the losses of the reactive nitrogen into the wider environment, namely rivers, lakes, oceans and the atmosphere. Estimates for this loss vary but typically, on a global average, only 30-40% of it goes into the crop.

This environmental impact manifests itself in three distinct ways. Firstly there is eutrophication of water bodies whereby algal blooms effectively 'suffocate' the aquatic life leaving at worst 'dead zones'. Notable examples of these are The Black Sea, The Gulf of Mexico, The Mississippi River Delta and Lough Neagh. Secondly ammonia loss following the use of nitrogen fertiliser, especially urea, leads to acid rain resulting in damage to natural habitats and finally there is the contribution that applied nitrogen makes to Green House Gas (GHG) emissions.

These emissions can be attributed to two areas, the manufacturing process and that following its application. The GHGs associated with manufacturing relate to either or both of nitric acid production and energy consumption. The largest hotspot in production is during nitric acid production for ammonium nitrate manufacture; however, modern plants are now equipped with 'abatement' technology that removes up to 90% of this nitrous oxide. With regard to the emission following application IPCC rules state that 1% of the applied nitrogen is emitted as the GHG nitrous oxide. This is now the area of focus to understand the accuracy of this figure and subsequently practices that can mitigate against this emission. It should be noted that this emission is not exclusive to manufactured nitrogen, it is appropriate for any form of reactive nitrogen applied e.g. manures, slurry, digestate.

The original Arden study working title, 'Life without manufactured nitrogen fertiliser' really stems from the fact that current manufacture is based on fossil fuels, predominantly natural gas and coal, which by definition are non renewable thus making it unsustainable. In considering this it is important to bring some perspective to the argument. The best estimates calculate that world nitrogen fertiliser manufacture consumes approximately

1.1% of global energy *(C.J. Dawson , J. Hilton 2011*) so from an energy point of view there are some much bigger wins to be made in other high energy consuming sectors.

If viewed in terms of the timeline for fossil fuels and, more critically, natural gas supplies, then with the recent findings of large banks of shale gas in the USA and China, then exhaustion of the feedstock is some years away. As Peter Odell states (Professor Emeritus of International Energy Studies, Erasmus University of Rotterdam): “The oft-heard notion that we are ‘about to run out of fossil fuels’ is quite simply a myth”. “We may confidently predict that renewables will, by 2050, still contribute less than 20% of total global energy supply”. Vaclav Smil voices a similar opinion and does not consider nitrogen or phosphate to be first tier concerns over the next 50 years. We can therefore forecast that manufacture of nitrogen from an energy consuming perspective is not under short, or medium term threat; however, it still remains the case that the feedstocks are non renewable.

If we assume that in the long term there has to be a switch away from the current feedstock then what alternatives are there? Over recent years there have been many examples of alternative energy sources to use to produce a manufactured fertiliser. Innovation will continue in this area with potential for very local farm units of production via wind turbines, biomass, and geothermal. The examples/pilot plants that are in existence currently tend to produce anhydrous ammonia as the fertiliser, which has its own issues in terms of operator safety and crop efficacy. There is also the long term potential for nuclear energy to play its part in fertiliser manufacture!

Finding alternative methods of production does not resolve the issue of continuing to load reactive nitrogen into the global nitrogen cycle. If this trend is to be reversed then a real focus is needed on nutrient recycling. There is evidence of this beginning to happen as biodigestion units are established with the digestate residue potentially replacing 5-6% of the nitrogen fertiliser market. Some farming businesses are looking towards reintroducing livestock onto the farm, turning feed into fertiliser (i.e. manure). Bed and Breakfast pigs are one such example.

If the livestock feed has come from a crop such as soya, lucerne, clover etc, then inert atmospheric nitrogen has been converted to reactive nitrogen by these plants, again loading ‘new’ nitrogen into the nitrogen cycle. The most effective farming system will be a closed ‘circular’ one that has recycling at its centre with a zero ‘farm gate’ nutrient balance. Other than livestock there are additional areas of focus for improving farm nutrient use efficiency through the use of green manure crops, and the reintroduction of crops such as the pulses into the rotation.

Of course, this approach to soil fertility is exactly what was practised during ‘life before manufactured nitrogen’. Every farm should make it a priority to have an Integrated Soil Fertility Management Plan to reduce its reliance on manufactured fertiliser, making it a more resilient business if either economic or environmental pressures curtail the use of manufactured fertiliser.

In view of the long term availability of nitrogen fertiliser, many novel breakthroughs may come prior to fossil fuel exhaustion. There is currently a 'race' between academic institutes funded by charitable organisations such as the 'Bill & Melinda Gates Foundation'. Two such institutes are the University of Alberta with the 'Good Lab' and Professor Giles Oldroyd at the John Innes Centre who are both looking to use transgenics (Genetic Management) to create nitrogen fixing cereals. Whilst the end result is similar, they are researching two different approaches. The 'Good Lab' is seeking to get one of the plant organelles (e.g. mitochondria or chloroplast) to be the new nitrogen fertiliser factory, whilst Prof Giles Oldroyd is looking to create the same symbiotic relationship that exists between legumes and Rhizobium to make cereal roots 'nodulate'. Some still consider this Biological Nitrogen Fixation to be a 'pipedream', but now that there is the potential to map a genome the size of the human in a day, such a dream could be a reality in a decade or two!

Having used this Arden study to consider nitrogen fertiliser and its future from a different perspective, I am left with the feeling that the underlying issue that will actually determine the way in which we use nitrogen is its environmental impact. Technology can and will deliver either new methods of manufacture based on renewable energy (but it will come at a cost), or Biological Nitrogen Fixation/genetic modification to improve Nitrogen Use Efficiency will become a reality. However it settles out, 9 billion people on this planet, plus many animals in the form of livestock and pets, means a lot of reactive nitrogen in the global nitrogen cycle which must be recycled as efficiently as possible within those people and animals otherwise it is lost and creates impact wherever it has come from.

Contents

	Page
Preface	1
Introduction	3
Life Before 'Manufactured Fertiliser'	4
When did 'Manufactured Fertiliser' enter agricultural systems?	6
The Global Nitrogen Cycle	9
The Benefits of Nitrogen	12
Agricultural Productivity	12
Environmental Productivity	13
The problem of Nitrogen	14
Eutrophication	14
Acid Rain	16
Green House Gas Emissions	16
Dependence on Fossil Fuels.	18
SECTION A. The Timeline for Manufactured Nitrogen Fertiliser	**20**
Nitrogen Fertiliser and Energy.	20
Fossil Fuel Exhaustion and The Concept of Peak Energy	20
The Potential Role of Renewable Energy.	25
Fertiliser from Wind Turbines	26
Fertiliser from Biomass	27
Nuclear Power and Fertilisers	29
Section A. Summary	30
Section B. Reducing the reliance on manufactured nitrogen fertiliser.	**31**
Alternatives to manufactured nitrogen.	31
Nuffield Study Visit - Rothamsted Research's Classical Experiments	32
Use of Organic Materials.	35
Livestock / Livestock manure	35
Biodigestate	36
Nuffield Study Visit - Bedfordia Farms utilisation of biofertiliser from AD.	38
Compost	40
Crop Rotation	40
Nuffield Study Visit - Institute of Organic Training and Advice (IOTA)	42
Green Manures	43
Mobile Green Manures.	49
Nuffield Study - Plant-based fertilisers for organic vegetable production	52
Improving nitrogen recovery by plants.	54
Nuffield Study Visit – CIMMYT	56
Triticale and improved NUE.	56
Nuffield Study Visit – Arcadia Biosciences	60
Nuffield Study Visit – University of Alberta	64
Biological Nitrogen Fixation.	66

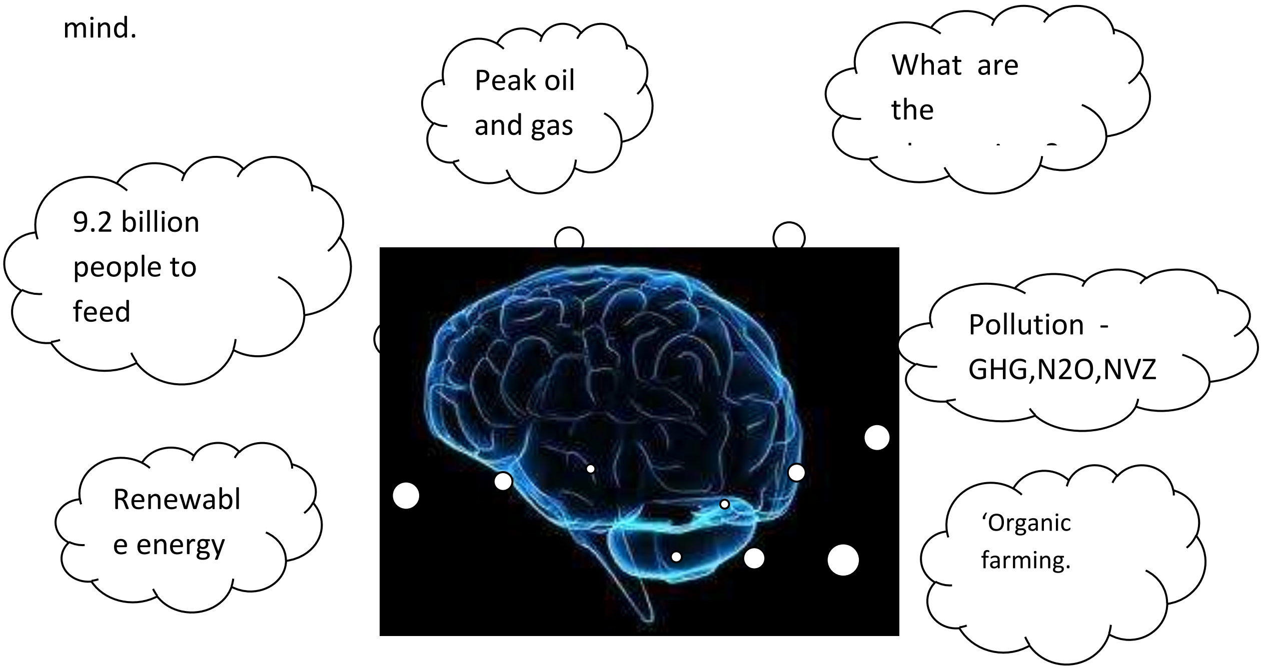
Nuffield Study Visit – The John Innes Centre 67
Improving the Nitrogen Recommendations. 68
Nuffield Study Visit – Beck Farms, Innisfail, Canada 69
The See Through Soil 70
DNA Finger printing of soils. 71
Improved Nitrogen Management via the Canopy. 71

Conclusions 74

Actions for UK Farmers 75

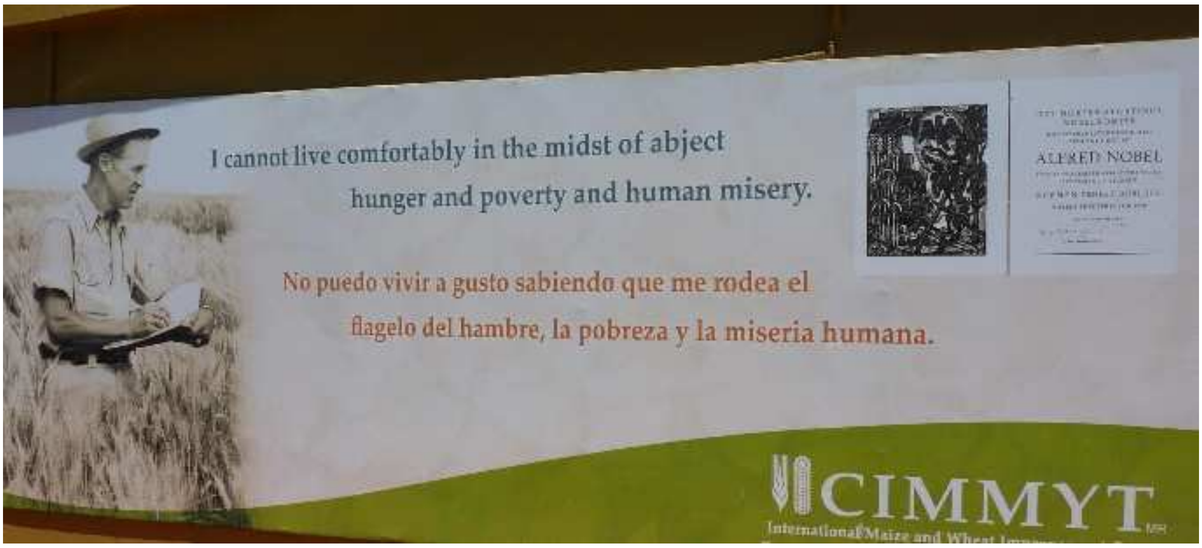
Preface

The original title of this report was ‘Life after manufactured fertiliser’ which is clearly quite a provocative, but fundamental statement that needs special consideration. The Nuffield Trust should be applauded for this as such a report enables all sides of the fertiliser argument to be addressed in the same arena. When posed with this question, individuals react in many ways some of which will be explored throughout the document. As I, on first seeing it, pondered the title, then the standard reactions/ideas of how do we feed the world?, will fertiliser ‘run out’? and if so when? what are the alternatives? - all came to mind.



Such diversity of thought starts to give the report its shape and issues to consider. However, the simplest and most useful starting point is to consider that ‘Life after manufactured fertiliser’ is the same as ‘Life before manufactured fertiliser’. This approach immediately focuses the subject towards looking back to how our forefathers farmed and how they managed their businesses without ‘manufactured fertilisers’. Of course it is wrong to intimate that they farmed without manufactured fertiliser as they did not, it was just a very different looking fertiliser factory to those of today – it typically had four legs and a tail, or was a plant! The question therefore that is raised by this report is what will the fertiliser factory of the future be – do we go back to a Circular Farming system whereby much better cycling of nutrients occurs with livestock, municipal waste, biodigestion, coming together to be the ‘fertiliser manufacturer’ of the future - or do we embark on the road to plant organelles becoming the fertiliser factory, which inevitably raises the issue of genetic modification?

My interest in Nuffield Scholarships was led by intrigue as Scholars such as Clive Blacker and David Gardner had urged me to consider it if the opportunity arose. With my being the wrong side of 45 this was unlikely. But then, along came the title of the Frank Arden Award 2011 and the rest is history. This opportunity has not only allowed me to contribute to a debate that is only going to grow and intensify with many competing arguments, but also to visit organisations such as CIMMYT, the home of Norman E Borlaug, a dream for many agronomists.



CIMMYT - the home of Dr. Norman E Borlaug (1914-2009) and a dream for many agronomists

Introduction

Fertiliser (or sulphur) is any organic or inorganic material of natural or synthetic origin (other than liming materials) that is added to a soil to supply one or more plant nutrients essential for the growth of plants. There are clearly a number of nutrients that come under the heading of fertiliser, which may be macro or micro. In total thirteen minerals are generally considered to be essential for plant growth and development (excluding carbon, hydrogen and oxygen).

- six macronutrients: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S);
- seven micronutrients: boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn).

The macronutrients are consumed in larger amounts and are present in plant tissue in quantities from 0.15% to 6.0% on a dry matter basis (DM). Micronutrients are consumed in smaller quantities and are present in plant tissue in the order of parts per million (ppm), ranging from 0.15 to 400 ppm DM, or less than 0.04% DM. Three other macronutrients are required by all plants: carbon, hydrogen, and oxygen. These nutrients are supplied by water and carbon dioxide.

Three have become synonymous with manufactured fertiliser, namely Nitrogen, Phosphate and Potash. Of these, two have become noted for their importance both in contribution to crop productivity, and also for their contribution to environmental degradation – nitrogen and phosphate. These two nutrients are also critically linked to finite resources, Phosphate being manufactured from mined rock phosphate and Nitrogen manufacture currently requiring a high input from fossil fuels – predominantly natural gas and oil. World fertiliser consumption continues to grow annually, however this does mask the fact that its consumption in Europe remains static, with the growth exclusively linked to the rest of the world – notably Asia.

This report covers the issues associated with Nitrogen fertiliser manufacture and its use, and then seeks to address the need for farmers to explore the opportunities available to reduce their reliance on fertiliser and use alternatives as they become available. It also explores the opportunities that may be decades away, but potentially have the most dramatic impact on the reduction in the use of fertiliser – plant breeding. The potential improvements in Nitrogen Use Efficiency (NUE) offered from the use of biotechnology (or more commonly known as Genetic Modification) is the area that leaves politicians, environmentalists, and the general public at a crossroads. The arguments to embrace this technology will be very compelling with the environmental opportunity combined with agronomic performance a hard one to resist.

Life before 'Manufactured Fertiliser'

Around the world farming systems developed with the main aim to maintain or increase soil fertility. This ensured that yields were either maintained or increased for generations, which is essentially the definition of sustainability. A number of systems emerged with our own Norfolk Four Course Rotation soon becoming well recognised for its ability to maintain soil health towards achieving optimised crop yield and quality. Interestingly it can be argued that this development was brought about by, again, a growing population that agriculture needed to respond to. In previous generations e.g. the Roman period, 1300, 1650 and 1750, the population was 5.7 million and remained static largely as a result of agriculture being unable to respond to the extra demand.

There are other examples around the world of such farming systems. One can be seen in Africa which has the world's oldest land mass. Many of Africa's soils are derived from ancient granite rocks and are therefore inherently low in plant nutrients. Compounding this natural deficiency, nutrients leach and are lost from the soil through cultivation, wind and water erosion, and harvest. Traditionally, African farmers have used fallows to maintain soil fertility by allowing fields to go back to bush for a number of years between periods of cultivation. The bush was cut and burnt; leaving ash for nutrients; a lower weed bank, and soil that is good for two or three years of cultivation. As the population increased over the 20th century, the cycles got shorter and soils became increasingly degraded. Fallowing is predicted to disappear entirely in the next few years. Due to lack of essential inputs, knowledge and incentives, traditional practices have not been replaced by new methods of soil management and cropping systems. Farmers' removal of the major plant nutrients and essential micronutrients for plant growth has not been offset by additions of nutrients; hence Africa's small-scale farmers are "mining" the soil. The International Centre for Soil Fertility and Agricultural Development estimates that Africa loses 8 million metric tons of soil nutrients per year, and over 95 million hectares of land have been degraded to the point of greatly reduced productivity. Such severe soil depletion results in a cycle of declining yields and increased degradation of the natural resource that farmers depend on. Soil mining leads to loss of soil organic matter. This loss reduces the soil's biodiversity and limits its ability to retain nutrients and water, and can lead to massive erosion. As soils decline and yields drop, farmers move on to clear forests, where the cycle begins again. This very same picture can be seen on your UK farms where phosphate and potash applications are not matching the annual offtake.

In contrast, healthy soils are a complex matrix of components like sand and clay, organic matter and living organisms. In this mix are molecules that play important roles in releasing nutrients such as nitrogen, phosphorous and potassium from organic matter, sand and clay. Once released into water-soluble forms, these nutrients can support plant growth. Improving soil health is essential to reverse the negative trends in food production and farm incomes. Organic matter management and precise use of fertiliser will help solve farmers' soil fertility problems. Integrated Soil Fertility Management (ISFM) combines the use of both to increase crop yield, rebuild depleted soils and protect the soil for the future. ISFM applies locally adapted soil fertility management practices to optimise the effectiveness of fertiliser and organic inputs in crop production.

Experience has shown that the highest and most sustainable gains in crop productivity per unit nutrient are achieved from mixtures of fertiliser and organic inputs *(Broadbulk 2012 data*). Manufactured fertilisers are concentrated chemical forms of plant nutrients, while organic materials from sources such as manure, crop residues, biodigestate and compost are much more complex materials.

There is no doubt that fertiliser application alone create big increases in yield, but generally with a low efficiency and its manufacture, based on fossil fuels, makes it environmentally unsustainable. Soil management practices to maintain soil quantity, structure, nutrients, and chemistry can be a partial alternative to the use of the mineral fertilisers but alone cannot meet nutrient demands. In combination, however, organic methods increase the efficiency of fertiliser and fertiliser helps increase the returns on organic methods through positive interactions on soil biological, chemical and physical properties.

There is no doubt that prior to manufactured fertiliser, farmers had soil fertility building at the heart of their enterprise. A farming system was adopted that used long term rotations, livestock, and manures to achieve this. A return to this position is essential if farming is to reduce its reliance on manufactured nitrogen. Having an Integrated Soil Fertility Management (ISFM) strategy should be a given on every farm.

When did 'Manufactured Fertiliser' enter agricultural systems?

Manufactured fertiliser, in terms of our regular understanding, entered farming in 1842 when Sir John Bennett Lawes produced the first industrial phosphorous fertiliser. At a similar time, in 1882, fertiliser production started in Sweden to meet the demands coming from Swedish and Danish agriculture. This production was as a result of Justus Von Liebig describing how rock phosphate could be reacted with sulphuric acid to produce a plant available nutrient. Prior to this, naturally occurring sodium nitrate, or Chilean Saltpeter, had been used in agriculture as a source of nitrogen. Interestingly it is reported that the first shipments of this came in to England in the early 1820s but no buyers were found with the consequence of it being dumped at sea to avoid a customs toll! By 1859 47,000 metric tonnes of Chile Saltpeter were being used as a fertiliser. Ironically this was a finite resource so as deposits began to dwindle alternatives would be required – 'life after Chilean Saltpeter' would have been a study topic then!

Potash has been used throughout history in various industrial processes (bleaching textiles and glass production) and was produced from leaching out the potassium from wood ash. The latter was a by-product of deforestation as land was cleared for agricultural use. This industry declined as large deposits of mineral salts containing potash were discovered in Germany and Canada. The commercial supply of mineral potassium fertilisers from these mines soon followed with Canada continuing to be the dominant force in world potash trade (see below).

Country	Production	Reserves
Canada	9.5	4400
Russia	6.8	3300
Belarus	5.0	750
China	3.0	210
Germany	3.0	150
Israel	2.1	40
Jordan	1.2	40
United States	0.9	130
Chile	0.7	70
Brazil	0.4	300
United Kingdom	0.4	22
Spain	0.4	20
Other countries		50
World total	33	9500

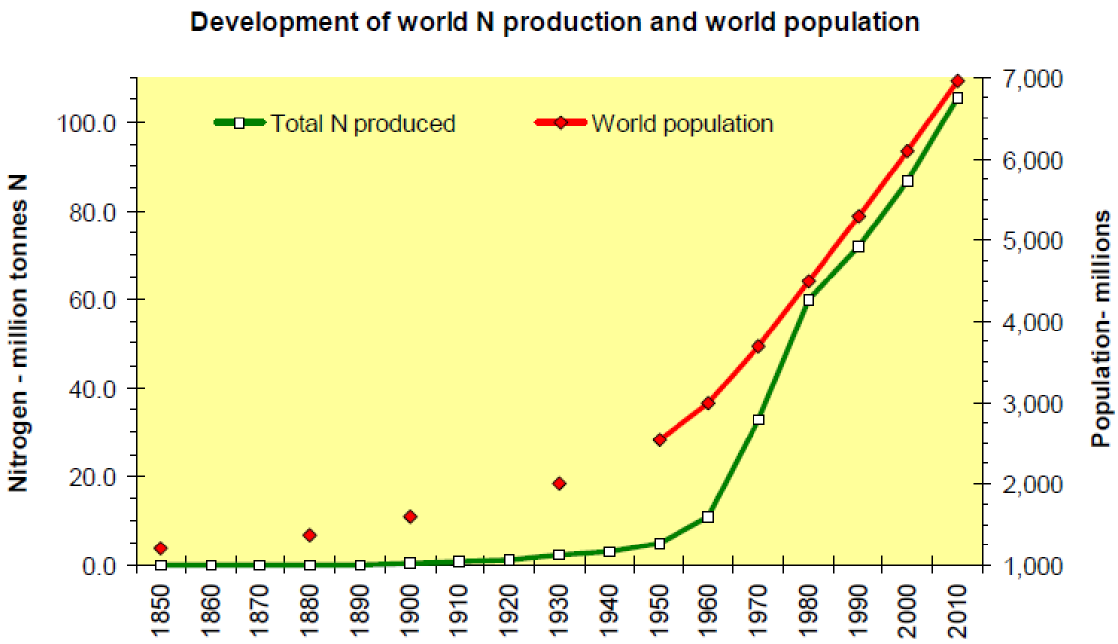
Wikipedia, Production and resources of potash (2010, million tonnes)

As already mentioned, nitrogen fertiliser, in the form of Chilean Saltpeter and guano (seabird excrement), was being used to enhance crop productivity throughout the 19th century, but as populations grew and the 20th century started there were increasing concerns over the ability of agriculture to meet the needs of these people. In 1898 British chemist William Crookes had exclaimed that , "England and all civilized nations stand in deadly peril of not having enough to eat", and claimed that adding nitrogen to the soil was the answer to increasing agricultural output. In November 1895 a German company (Die Deutche Ammoniak-Verkaufs-Vereinigung (DAW)) produced ammonia from nitrogen found in coal leading them to be Europe's leading fertiliser supplier. However, concerns grew and again it was Crooke who had referred to the possibility of fixing atmospheric nitrogen, that started new research into finding the technology to make this happen. In May 1905 the first "Norwegian Nitrate" was produced using the Birkeland-Eyde method. This method was developed by the Norwegian industrialist and scientist Kristian Birkeland along with his business partner Sam Eyde in 1903, based on a method used by Henry Cavendish in 1784! The process, whilst being successful, proved to be relatively inefficient in terms of the amount of energy required - 15 MWh/Ton of nitric acid produced. In the meantime the German chemist Fritz Haber was demonstrating the synthesis of ammonia, and after teaming up with Carl Bosch and BASF, developed ammonia production technology. The first Haber-Bosch ammonia plant was started in 1913. Almost all the manufactured nitrogen is now produced using this process. Life with manufactured nitrogen fertiliser had begun and man's intervention in the Global Nitrogen Cycle had moved to a new level.

Year	Haber-Bosch Synthesis of NH_3	Other syntheses	Total nitrogen	Haber-Bosch share (%)
1900	-	0.1	0.1	0
1910	-	0.7	0.7	0
1920	0.2	0.8	1.0	20
1930	0.9	1.2	2.1	43
1940	2.2	1.0	3.2	69
1950	3.7	1.1	4.8	77
1960	9.5	1.8	11.3	84
1970	30.2	1.4	31.6	96
1980	59.3	1.3	60.6	98
1990	76.3	0.8	77.1	>99
2000	85.1	0.6	85.7	>99
2010	100.0	0.5	100.5	>99

Data from Smil (2001) and International Fertilizer Association.

Global nitrogen fertiliser use continues to grow today at a rate of between 3 and 5% per annum (*Yara internal data*), although this growth is very much associated with developing countries in Africa and Asia, as European demand has reached a plateau. This swing in power has happened over the last 50 years. In 1960/61 the developing countries consumed 12% of world fertiliser which had changed to 70% by 2005 (see below).



World nitrogen production by source and process, ktN

Fertiliser year	Chilean nitrate	Guano	Coke-oven ammonium sulphate	Calcium cyanamide	Electric arc Ca nitrate	Synthetic ammonia	Total	Population (millions)
1850	5	-	-	-	-	-	5	1,200
1860	10	70	-	-	-	-	80	
1870	30	70	-	-	-	-	100	
1880	50	30	-	-	-	-	80	
1890	130	20	-	-	-	-	150	
1900	220	20	120	-	-	-	360	1,600
1910	360	10	230	10	-	-	610	
1920	410	10	290	70	20	150	950	
1930	510	10	425	255	20	930	2,150	
1940	200	10	450	290	-	2,150	3,100	
1950	270	-	500	310	-	3,700	4,780	
1960	200	-	950	300	-	9,540	10,990	
1970	120	-	950	300	-	30,230	31,600	
1980	90	-	970	250	-	59,290	60,600	
1990	120	-	550	110	-	76,320	77,100	
2000	120	-	370	80	-	85,130	85,700	6,100

Development of world nitrogen production. (C.J. Dawson , J. Hilton 2011).

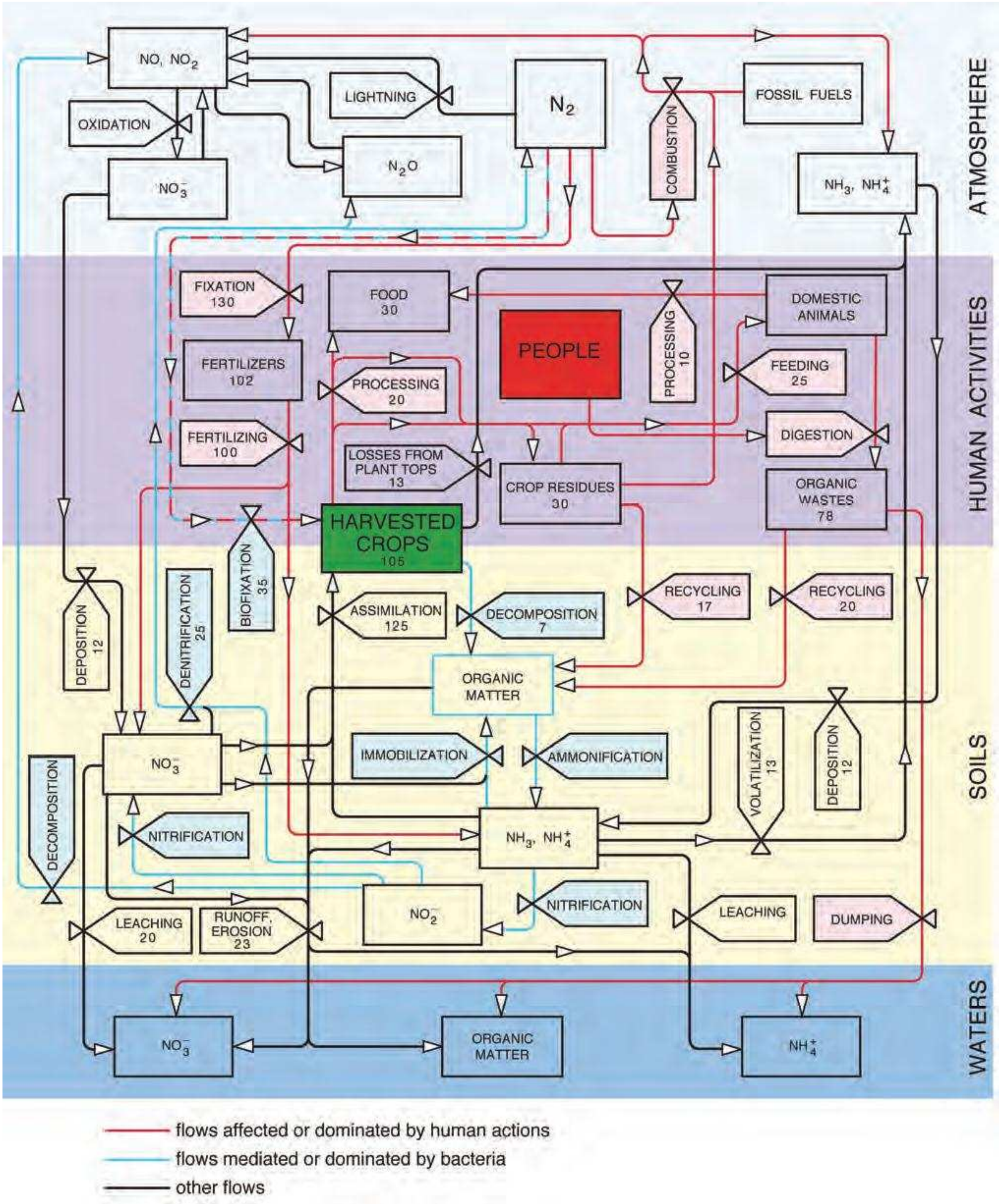
The Global Nitrogen Cycle

Over recent years we have all become very familiar with terminology associated with Climate Change with many references to the biosphere and the cycles that occur within it. Such cycles that have great relevance and importance for agriculture are the water cycle, carbon cycle, nitrogen cycle and phosphorus cycle. Until recently it has been the carbon cycle that has had most coverage. Interestingly the amount of human induced (anthropogenic) carbon emission is less than 10% of the carbon uptake of plants through the natural process of photosynthesis. By contrast human activities (e.g. fertiliser application and leguminous cropping) emit as much reactive nitrogen as do the natural processes of bacterial fixation and lightning.

'Reactive nitrogen' is the term used for all nitrogen that is no longer in its inert N_2 state, but instead in a chemically reactive state e.g. nitrate, ammonia, ammonium. The same problems exist whether the nitrogen is entering the cycle through a natural process or synthetically produced products – as all living organisms contain nitrogen, and the more there are of these whether people, animals or soil bacteria, the more reactive nitrogen there is. The choice that exists really comes down to which system adopted is the most efficient at delivering the amount of nitrogen required to support the maintenance of this 'life'.

The success of mankind to embrace the technology developed in the early part of the 20th century and thus load this nitrogen cycle has enabled the planet to support the population in its current state and potentially support a further 3 billion people in the next 3-4 decades. The global nitrogen cycle is a very complex one and can be seen detailed diagrammatically below *(Smil, 2008).*

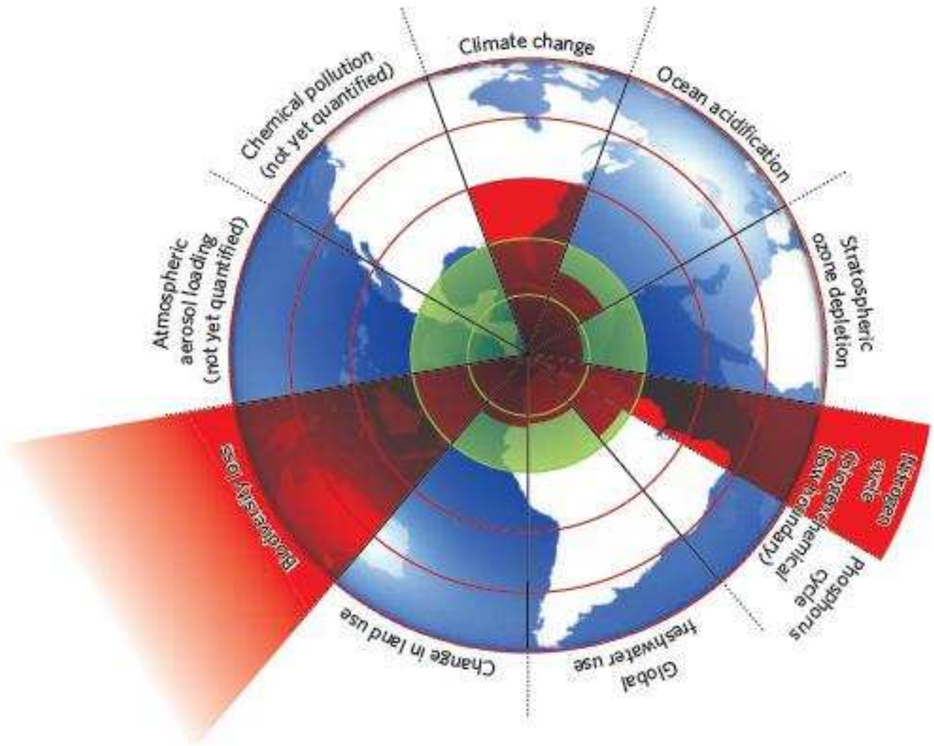
See diagram of the global nitrogen cycle (Smil, 2008) on next page



The Global Nitrogen Cycle(Smil,2008)

This agricultural productivity has come off approximately 15% of the ice free global land mass. Without the adoption of the Haber-Bosch process this figure would be four times as large at nearly 50%. Other authors have documented this agricultural intensification to have prevented 161 Gigatonnes of carbon emission, assuming that agriculture had expanded in its endeavour to feed the growing population (*Burney et al. (2010); Stanford Univ).*

The potential impact that such a human interference has had on one of the natural cycles is leading scientists to consider a new approach to understanding the framework within which we can exist that prevents the current relatively stable global environment from becoming unstable. The proposal has been to set ten 'Planetary Boundaries' which identifies the current status, the proposed boundary and what the Pre-industrial value was. Two of these 'Planets' are related to fertiliser – The Nitrogen Cycle and The Phosphorus cycle, with the former already in the 'red' zone.*(Rockström et al),*.



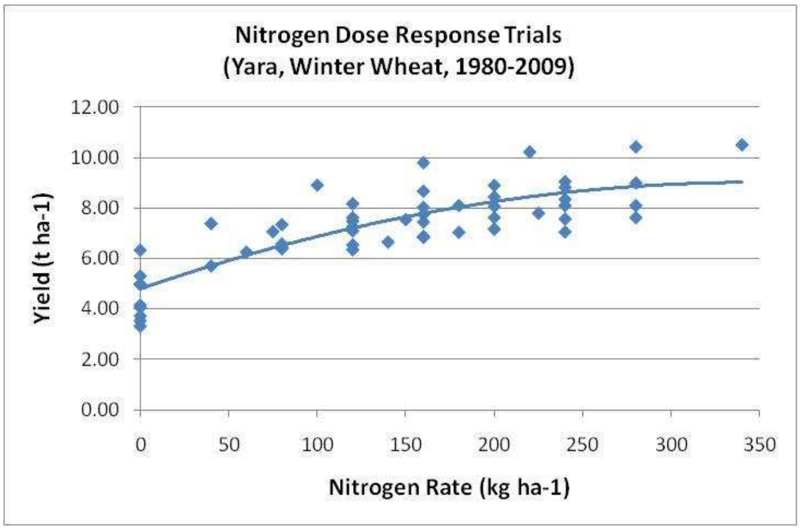
Beyond the boundary. The inner green shading represents the proposed safe operating space for ten planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded. (Rockström et al)

In order to understand how agriculture has to respond to reducing the loading of reactive nitrogen into this cycle it is important to understand clearly why agriculture and the world have become so reliant on it as an input. This then needs to be put into context with the negative impacts that such an input has on its environment. The next two sections will identify some of these issues.

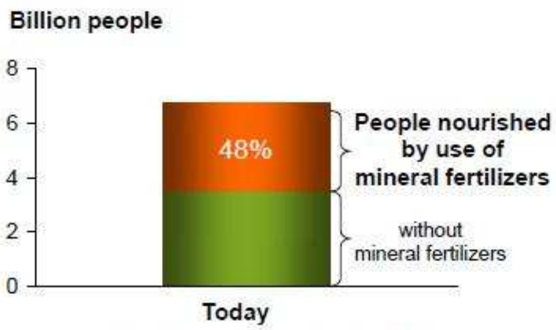
The Benefits of Nitrogen

Agricultural Productivity

Fundamentally agricultural systems around the world have developed to deliver affordable, high quality energy and protein to the human population. This can either be at the local, subsistence farming level of production or at the industrialised level whereby very sophisticated farming systems have developed to supply large, urban populations with the food that they demand. Both these farming systems are dependent on the level of nitrogen that is contained and recycled within it. If losses are occurring, inevitably, if yields are to be maintained, 'new' nitrogen has to be introduced. Whether crops of wheat, rice, corn or potatoes are being grown, applications of nitrogen will typically double the yields achieved.



It is for this reason that calculations have shown that manufactured nitrogen fertiliser now supports 48% of the world population:



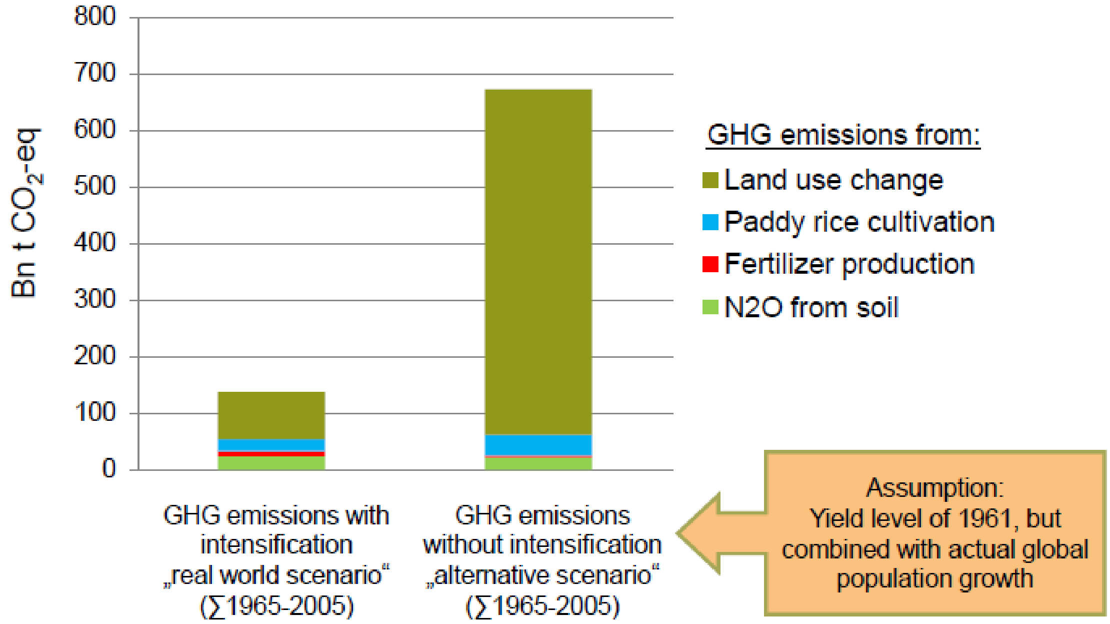
Source: adopted from Erisman et al. (2008), Nature Geoscience

Environmental Productivity

With arable land being a scarce and declining resource and to allow precious habitats throughout the world to be maintained or enhanced, intensive agriculture focuses food production on the appropriate land. This approach has been described as Sustainable Intensification (Reaping the benefits). Agricultural intensification has been a continual process as new technologies and economics have driven farmers around the world to seek improvements in productivity per unit of land. *Burney et al 2010* reviewed the mitigation of Green House Gases through agricultural intensification from the period between 1961 and 2005. They concluded that while emissions from factors such as fertiliser production and application have increased, the net effect of higher yields has avoided emissions of up to 161 gigatons of carbon (GtC) (590 GtCO2e) since 1961.

They estimated that each dollar invested in agricultural yields has resulted in 68 fewer kgC (249 kgCO2e) emissions relative to 1961 technology.

The increase in agricultural productivity since 1965 has saved more than 500 Bio tons of CO2 globally



Source: Burney et al. (2010); Stanford Univ.

The Problem of Nitrogen

The word 'problem' has been associated with nitrogen in two completely different ways over the last century. In the years prior to its industrial manufacture and the Haber-Bosch process the problem element was one of not having enough reactive nitrogen within the cycle to be able to support a growing population. This limit effectively acted as a break on population increase. As industrial production increased, nitrogen as a limiting factor was removed, and food production could increase in line with the demands of the growing population.

With the current poor nitrogen use efficiency in agriculture, leakage of this reactive nitrogen into the wider environment is inevitable and has lead the 'problem' to be now one of excess. Excess nitrogen entering the environment leads to three widely recognised issues, namely:

Eutrophication

acid rain

Green House Gas emissions.

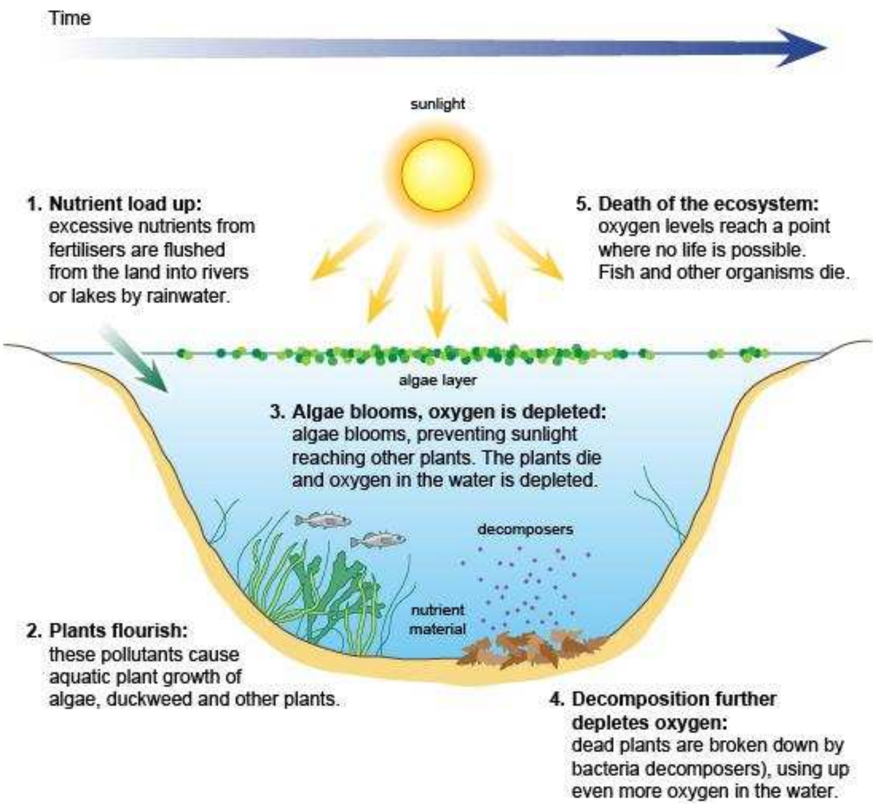
Finally from a sustainability issue, fertiliser manufacture is very dependent on the use of fossil fuels.

Eutrophication

Definition:

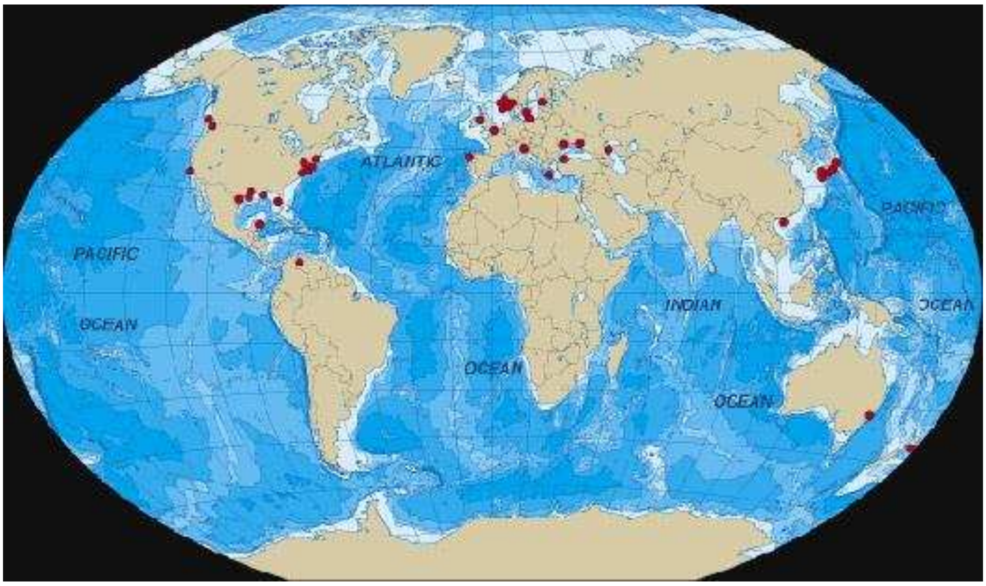
> '..eutrophication is an increase in the rate of supply of organic matter to an ecosystem. For marine scientists, eutrophication is "used simply to mean 'enhanced nourishment' and refers to the stimulation of aquatic plant growth by mineral nutrients, particularly the combined forms of phosphorus or nitrogen" '.

As previously described, the loading of reactive nitrogen into the environment has increased dramatically since the manufacture of nitrogen fertiliser. More nitrogen is fixed now through manufacturing than is fixed through natural microbial activity. Unfortunately the efficiency of uptake of plant nutrients is not 100%. With regard to nitrogen, global efficiency of use is typically 30-40% thus rendering 60-70% at risk to loss into the environment. Some of this loss will be through run off from soil surfaces and leaching down through the soil profile. Both of these lead to nitrogen entering the aquatic environment – rivers, lakes and oceans, where it can result in eutrophication.



*Diagrammatic representation of eutrophication (*www.bbc.co.uk*)*

Eutrophication eventually leads to a catastrophic breakdown of the aquatic ecosystem resulting in ocean 'dead zones' around the world.



Ocean 'dead zones' associated with eutrophication.
*(*http://disc.sci.gsfc.nasa.gov*)*

Examples of this problem have been well documented with the most notable being:

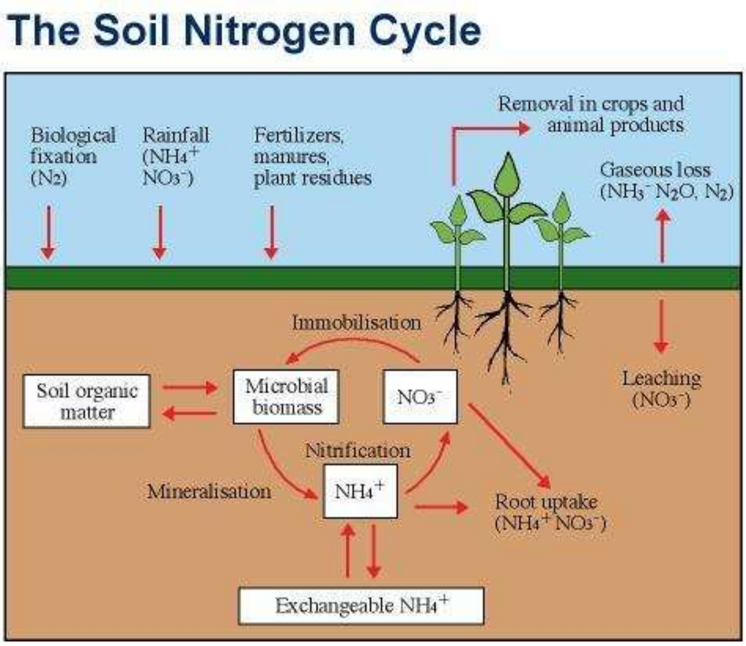
- The Black Sea
- The Gulf of Mexico
- The Mississippi River Delta
- Lough Neagh

Acid Rain

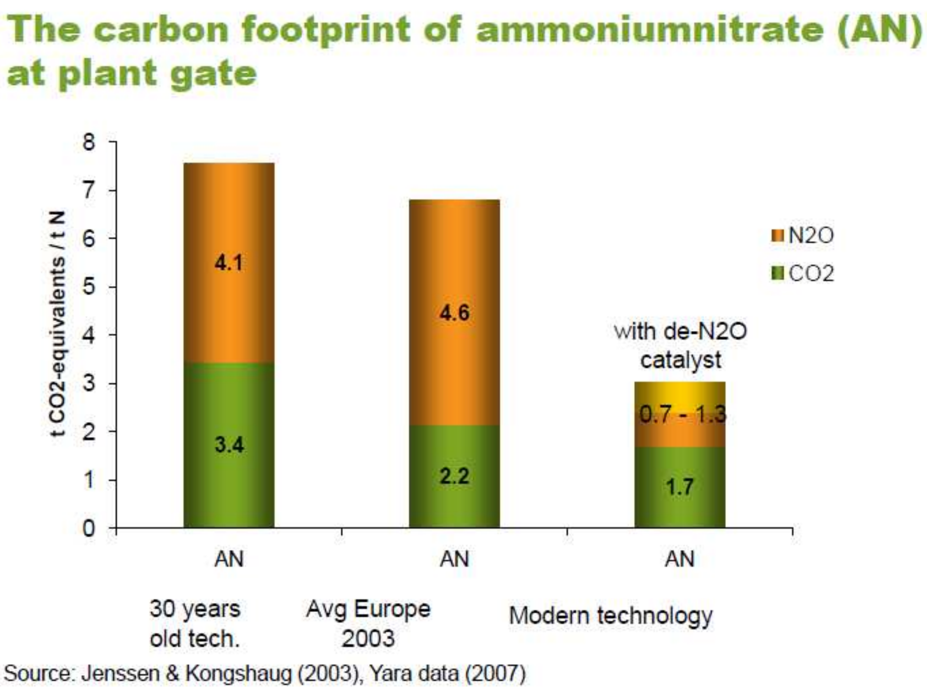
Acid rain is a rain or any other form of precipitation that is unusually acidic, meaning that it possesses elevated levels of hydrogen ions (low pH). It can have a harmful effects on plants, aquatic animals, and infrastructure. Acid rain is caused by emissions of sulphur dioxide and nitrogen oxides, which react with the water molecules in the atmosphere to produce acids. The role that nitrogen plays is particularly associated with the use or production of ammonia. If ammonia is used as a fertiliser then during its conversion to nitrate, NOX (Nitrogen Oxide) is emitted that forms acid in the atmosphere. If urea fertiliser is used then during this conversion ammonia is produced prior to transformation to nitrate, again resulting in NOX emission.

Green House Gas Emissions

Climate change is linked to the accumulation of a number of Green House Gases in the atmospheric environment, two of which are strongly linked to agriculture. These are methane and nitrous oxide with the former linked to livestock production and the latter associated with the soil nitrogen cycle. The use of nitrogen, inorganic or organic, fertiliser contributes to the quantity of Nitrous Oxide that is released from soils. Nitrous Oxide is approximately 300 times more powerful than carbon dioxide as a GHG.



With regard to nitrous oxide there are two aspects relating to the use of fertiliser. Firstly there is the emission of nitrous oxide during the production of nitric acid, the precursor to ammonium nitrate, and secondly is the emissions from soil following its application. Considering the emission during manufacture this has been recognised by the industry and investment over the last decade has gone into research to provide a solution to this problem. The solution was found in the form of a catalyst that converts approximately 90% of this emission of N_2O back to the inert N_2 and O. This technology is referred to as 'abatement' and is being fitted to many of the nitric acid plants. Following the instalment of this technology, the GHG emission and carbon footprint are dramatically reduced *(see graph below).*



Further improvements in the catalyst technology are expected to reduce these emissions further.

The second hot spot of emission is following the application of any reactive nitrogen products, whether organic or inorganic. This emission is recognised within IPCC calculations which states that 1% of applied nitrogen will be emitted as N_2O. The actual amount is a function of soil moisture content (aerobic vs anaerobic), soil temperature and amount and form of nitrogen applied.

The science and validity of these emissions is central to many research projects currently. The Min-No Link project is one such example.

Dependence on Fossil Fuels

Nitrogen manufacture requires a source of energy in order to combine the inert nitrogen from the air with hydrogen to produce ammonia. Currently the sources of energy and hydrogen used in the process are based on the fossil fuels – predominantly natural gas and coal. It is estimated that the ammonia manufacturing industry uses approximately 3-5% of global natural gas which equates to approximately 1.1% of energy consumption.

World, EU and UK use of energy, overall and for fertiliser production

Annual use of energy		World 2008	EU27 2008	UK 2008
Total energy use	PJ	515,000	76,420	9,609
Energy for production of fertiliser used	PJ	5,850	481	44*
Fertiliser use as % of total	%	1.1%	0.6%	0.5%

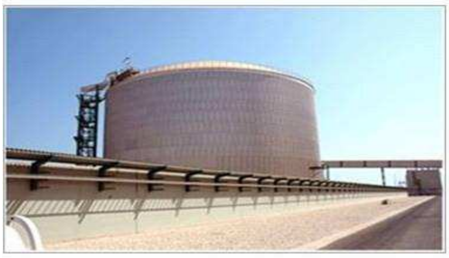
* includes packaging and distribution.

Source:C.J.Dawson

By definition these fossil fuels are non renewable, thus rendering the current manufacturing unsustainable. The consideration therefore has to be towards alternative ways of producing reactive nitrogen. However this will be a challenge as the current manufacturing, whilst being defined as unsustainable, is now a very efficient process, with the use of natural gas consuming one third of the energy compared to water electrolysis.

See the diagram headed Reaction Stoichiometry on next page

The challenge clearly is to find a method of using renewable energy in the production process. Large amounts of investment have gone into the energy efficiency of these modern manufacturing plants with the largest ammonia and urea factory recently commissioned being QAFCO-5 at $3.2 billion. This continued investment has led to very energy efficient plants as **shown in the second diagram on the next page**:



Sheikh Tamim Bin Hamad Al-Thani, the Qatari Heir Apparent, on Tuesday inaugurated the $3.2 billion QAFCO-5 project in the industrial city of Mesaieed. The project will make QAFCO the world's largest single site producer of ammonia and urea.

Reaction stoichiometry

Fuel

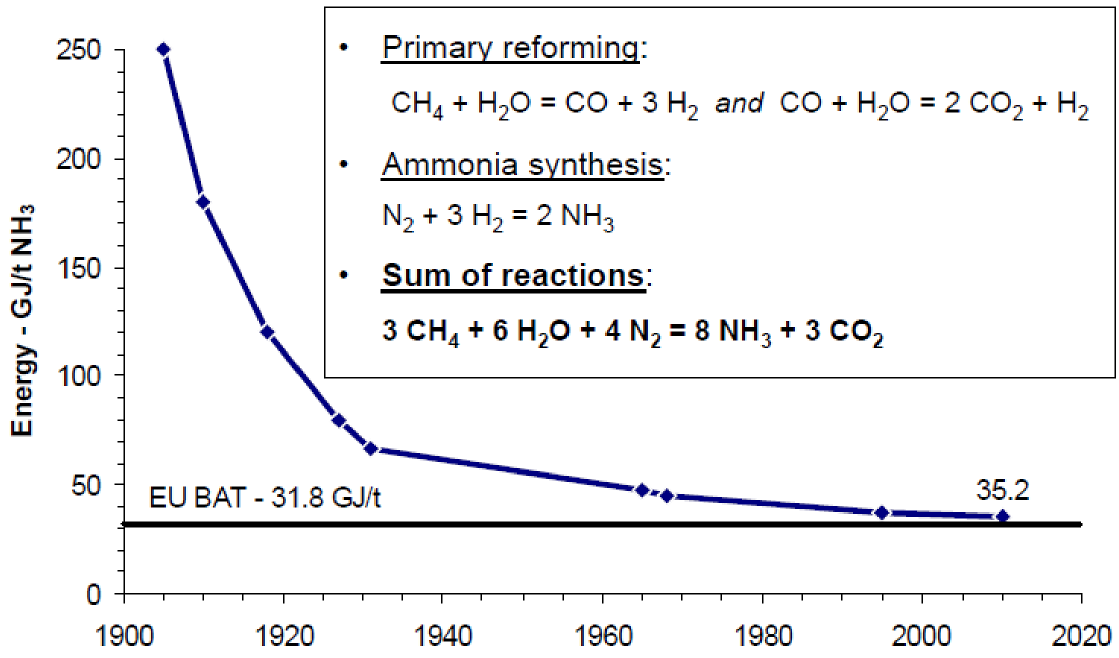
Process	Combustion reaction	GCV GJ/kmol	kg CO_2 per GJ GCV	NCV GJ/kmol	kg CO_2 per GJ NCV
Methane	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	0.89	49	0.8	55
Ethane	$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6\ H_2O$	1.56	56	1.43	61
Propane	$3C_3H_8 + 15O_2 \rightarrow 9CO_2 + 2H_2O$	2.22	60	2.04	65

Feedstock

Relative energy use	Process	Reaction	C:H in feed	$CO_2:H_2$ in product	% H_2 derived from water
300	Water electrolysis	$2H_2O \rightarrow 2H_2 + O_2$	0:1	0	100
100	Nat. gas reforming	$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	1:4	0.25	50
	Propane reforming	$C_3H_8 + 6H_2O \rightarrow 10H_2 + 3CO_2$	1:2.6	0.3	60
104	Naphtha reforming	$CH_2 + 2H_2O \rightarrow 3H_2 + CO2$	1:2	0.33	66
170	Coal Gasification	$C + 2H_2O \rightarrow 2H_2 + CO_2$	1:0	0.5	100

GCV (gross calorific value) = HHV (higher heating value)
NCV (net calorific value) = LHV (lower heating value)
NCV/LHV excludes the heat of vaporisation of the moisture in combustion products

Reduction in energy use for ammonia production and the process reactions



Section A: The Timeline for Manufactured Nitrogen Fertiliser

Throughout the report so far I have highlighted the various issues that surround nitrogen fertiliser showing that on the one hand it delivers benefits through the improved agricultural productivity and therefore alleviation of hunger throughout the world, whilst the excessive reactive nitrogen that is now apparent in the global nitrogen cycle is leading to the degradation of important ecosystems and contributing towards Climate Change through the associated N_2O emissions. The manufacture of nitrogen is also problematic with its reliance on intensive energy use coal, oil and natural gas – all of which are finite resources. All of this is the background to the original title of this report which questioned the length of time that manufactured nitrogen fertiliser will remain an essential farm input.

Clearly there are four possible outcomes for its fate:

1. It continues to be used as the benefits are considered to outweigh the disadvantages as the short/medium term demands on agriculture to be the supplier of both food and fuel.
2. Environmental damage attributed to reactive nitrogen is considered to be too damaging/costly so restrictions on its use gradually remove it from agricultural production systems.
3. The fossil fuels that its production relies on are exhausted and assuming no economically viable alternative has been developed fertiliser manufacture ceases.
4. New production systems that no longer rely on non renewable fuels are developed improving the environmental footprint, and together with improved crop production systems reliance is reduced to a minimum or zero depending on long term biotechnology developments.

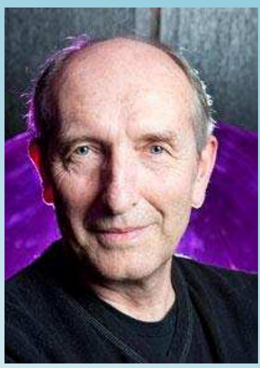
The rest of the report will be devoted to looking at these issues and exploring the ways that farming can reduce its reliance on manufactured nitrogen fertiliser, many of which I have encountered during my Nuffield journey.

Nitrogen Fertiliser and Energy

Fossil Fuel Exhaustion and the Concept of Peak Energy

Assuming no technological advancement and no new alternatives then one of the potential scenarios that would affect the long term availability of manufactured nitrogen fertiliser is the exhaustive nature of fossil fuels. This finite position means that there will be an absolute need to have alternative approaches. The question then becomes how long does the world have to seek these alternatives? Such a discussion needs to consider the concept of peak energy. This can be described as the point in time when the maximum global production rate has been achieved, after which a gradual, terminal decline occurs. Eventually production comes to an end and alternatives have to be used.

As part of my Nuffield study my first area to consider was the peak energy concept so I made contact with Dr. Vaclav Smil. Dr Smil is currently a Distinguished Professor in the Faculty of Environment at the University of Manitoba in Winnipeg, Canada. He is considered to be one of the world's leading experts in energy. His interdisciplinary research interests encompass a broad area of energy, environmental, food, population, economic, historical and public policy studies, and he had also applied these approaches to energy, food and environmental affairs of China. He has been an invited speaker in more than 250 conferences and workshops in the USA, Canada, Europe, Asia and Africa, has lectured at many universities in North America, Europe and East Asia and worked as a consultant for many US, EU and international institutions. He has published more than 30 books and approximately 400 papers. My first contact immediately revealed an interesting view on this subject (see insert).



"Indeed, my influence might be most undesirable, as I believe that given a relatively small share of global energy needed for Haber-Bosch and the enormous opportunities for cutting waste and rationalizing energy use in every other sector we will have no resource constraints on synthetic ammonia for generations to come (assuming the atmosphere does not get evaporated in a thermonuclear war), and also that P capture and recycling, and better applications combined with much larger resources out there (see the latest Muscle Shoals report) does not mean any imminent P peak. So not total complacency, but certainly no urgency in contemplating life without fertiliser"

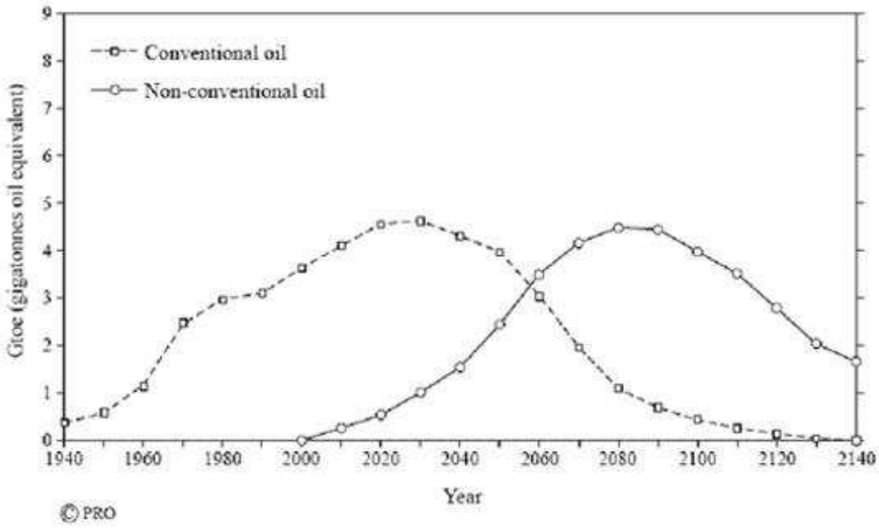
".. I consider both N and P as not even the first-tier concerns for the next 50 years (for what I do worry about see my Global Catastrophes and Trends"

Vaclav Smil, Dec 2011

Recommended Viewing: **http://www.youtube.com/watch?v=678b7N0pIHE**

Further research and contact with Vaclav and his many writings on the Energy issues revealed that the forecasts vary enormously. The ultimate pessimist appears to be Richard Duncan who described his 'Olduvai Gorge theory' whereby peak oil was 'a turning point in human history', and that its effect would start in 2025 ending with civilisation back to where it was 2.5 million years ago! The most reported 'Peak Oiler' is M.King Hubbert who has had many attempts at predicting when the global peak of oil/gas is likely to occur. This figure varied from 25 billion barrels p.a. in 1990 to 37 billion barrels p.a. in 2000. Hubert's Peak Theory falls down further as it then assumes an exponential response such that once the peak occurs you can extrapolate how long before the resource is exhausted. Thus if the peak is wrong then the decline to exhaustion will be wrong and also the documented evidence suggests that declines do not follow the 'bell shape', but more a long plateau followed by a decline. The other assumption that brings further inaccuracy to such models is that we know the levels of recoverable oil, and assumptions about recovery rates tend to be fixed.

However on both these issues the figures are largely unknown. Not only are new reserves being found but also recovery rates are increasing to around 40%, compared to the 30% of two generations ago. Such models cannot predict the reduced demand and either that technology brings improved efficiencies, or complete replacements. A classic example of this is the car industry which is constantly bringing new, more fuel efficient cars to the market. The latest predictions for the decline in oil extraction put the peak to be around 2020–2030 with a plateau, followed by a decline with production back to 2010 levels in 2070.



Source: Energy – Myths and Realities, V.Smil

Of course oil is not the only fossil fuel and hence energy source for fertiliser production, there is coal and natural gas. If we therefore consider these within this discussion then the dominance of carbon based fossil fuels looks set to remain throughout the 21st Century. In January 2010, Peter Odell (Professor Emeritus of International Energy Studies, Erasmus University of Rotterdam) set out his predictions for 2100 stating that of the total energy supplies, 30% will be natural gas, 28% renewable, 20% oil and 20% coal.

Another guru on the energy debate is Peter Odell, who again appears to have rather less concern than some would have us believe.

"The oft-heard notion that we are "about to run out of fossil fuels" is quite simply a myth"

"We may confidently predict that renewables will, by 2050, still contribute less than 20% of total global energy supply"

Peter Odell is Professor Emeritus of International Energy Studies, Erasmus University of Rotterdam

With these conclusions from such leading experts and establishments, it can be concluded that the supply of fossil fuel energy throughout this century is not an issue; however, the consequences of such continued high use in view of Climate Change possibly is. To conclude this section of my report it is worth noting which countries hold the key to these fuels and also how much of this fossil fuel is used in the manufacture of nitrogen fertiliser. Firstly from the tables below taken from International Energy Agency report 2011 the power clearly lies with the Russian Federation for oil and gas, whilst China has the power with coal.

OIL

Producers	Mt	% of world total
Russian Federation	502	12.6
Saudi Arabia	471	11.9
United States	336	8.5
Islamic Rep. of Iran	227	5.7
People's Rep. of China	200	5.0
Canada	159	4.0
Venezuela	149	3.8
Mexico	144	3.6
Nigeria	130	3.3
United Arab Emirates	129	3.2
Rest of the world	1 526	38.4
World	**3 973**	**100.0**

2010 data

Natural GAS

Producers	bcm	% of world total
Russian Federation	637	19.4
United States	613	18.7
Canada	160	4.9
Islamic Rep. of Iran	145	4.4
Qatar	121	3.7
Norway	107	3.3
People's Rep. of China	97	3.0
Netherlands	89	2.7
Indonesia	88	2.7
Saudi Arabia	82	2.5
Rest of the world	1 143	34.7
World	**3 282**	**100.0**

2010 data

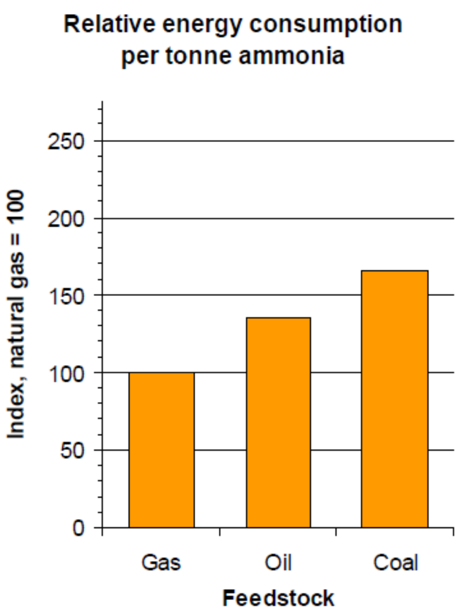
COAL

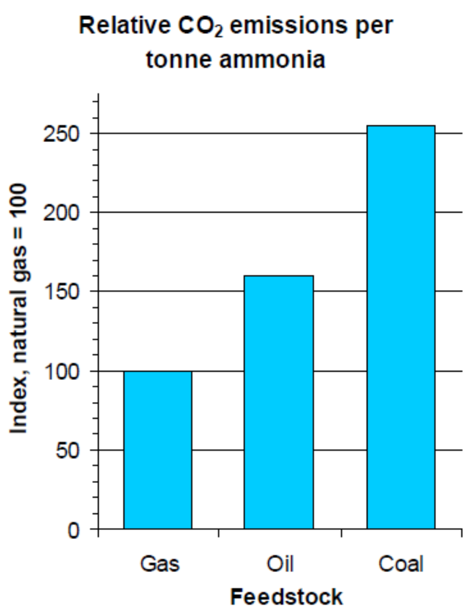
Producers	Hard coal* (Mt)	Brown coal (Mt)
People's Rep. of China	3 162	**
United States	932	65
India	538	33
Australia	353	67
South Africa	255	0
Russian Federation	248	76
Indonesia	173	163
Kazakhstan	105	6
Poland	77	57
Colombia	74	0
Rest of the world	269	576
World	**6 186**	**1 043**

2010 data

Source: International Energy Agency report 2011

So how much of this energy is used in the manufacture of nitrogen fertiliser? In terms of the amount of primary energy that is used in the manufacture of nitrogen fertiliser then it is typically quoted at between 1.1%, this compares to 62% that is consumed by global transportation. For this energy cost we get in return around 48% of the worlds food production. The fossil fuel in the manufacturing process is used for two elements: firstly as energy to actually drive the processes involved i.e. the Haber Bosch process which requires high temperatures and pressures to operate. The second element of the process is the requirement for hydrogen to be combined with the nitrogen in the production of ammonia. The dominant source of hydrogen is from natural gas. 3–5% of world natural gas production is consumed in the Haber process and continues to be the most energy efficient and cleanest feedstock to use.





Data from Fertilizers Europe

Kusters and Lammel (1999) analysed the return in respect of energy. When using field data they calculated that the extra 3.5t/ha wheat yield advantage from using 170 kgN/ha returned an extra 55GJ/ha of energy, some six times the 8GJ/ha required to produce, transport and apply the nitrogen fertiliser.

Clearly the critical point is to make best use of this captured solar energy to replace fossil fuel energy. If the longevity of nitrogen manufacture is determined by the availability of energy and a hydrogen source then clearly an area to investigate for future development is the use of alternative energy and hydrogen sources.

The Potential Role of Renewable Energy

Renewable Energy in perspective (Source: Smil).

- World primary energy consumption is about 14 terawatts (TW), or about 2.2 kilowatts (kW) per person.
- Solar energy is by far the largest ultimate source of energy available for human use (other sources include geothermal and fission power). The Earth intercepts 170,000 TW of power from the sun
- Wind power is about 200 TW worldwide

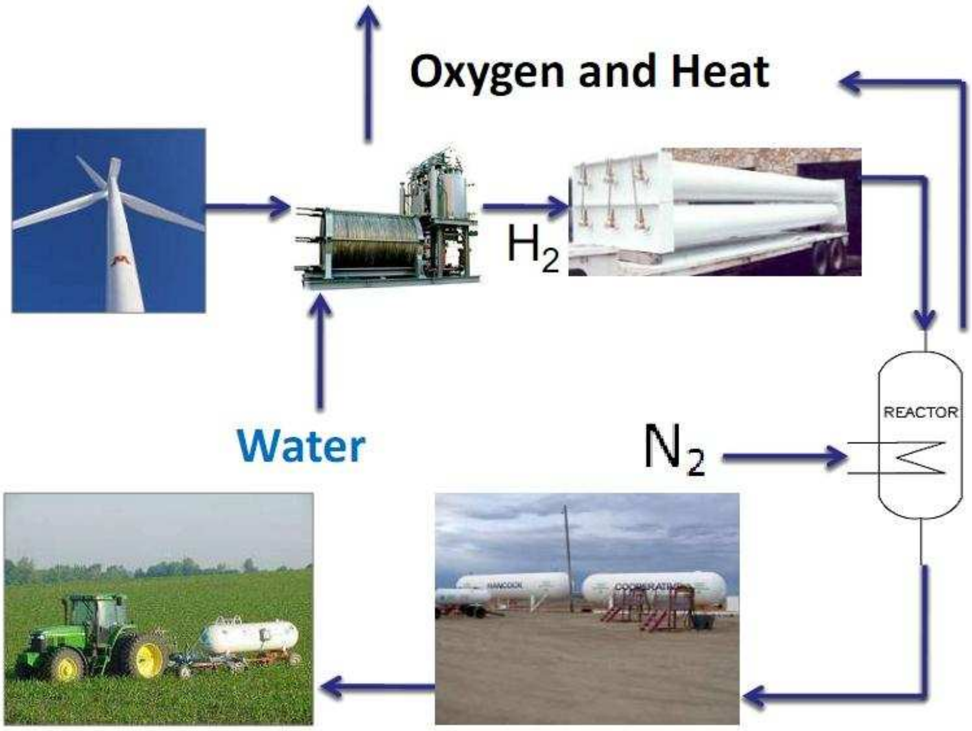
If we consider nitrogen fertiliser in its simplest, nitrate, form it consists of three critical components, namely nitrogen, oxygen and energy. Two of these are clearly in great abundance, all around us; nitrogen makes up 78% of air whilst oxygen 21%. The third ingredient, energy, is the potentially scarce resource. We can add a fourth element, hydrogen, if we want to make ammonia based fertiliser. With this in mind it is feasible to consider that in the absence of fossil fuels, then renewable energy could be a feature of future nitrogen production. If we look back over the last century then numerous projects and writings have covered this topic and indeed proven that renewable energy could be utilised. Back in March, 1922, the New York Times reported on 'Food from the Air', discussing the use of hydroelectric power to create the electric arc needed to combine nitrogen and oxygen into nitrate (this happens naturally through the lightning process). A return to this process, that was commercialized in 1905 in Norway (the Birkland-Eyde process), could be one possibility. Other renewable energies are now under investigation with pilot studies on wind turbines and biomass happening in the US.

The more controversial, but potentially most efficient alternative is nuclear fuel as the source of energy, and hydrogen via electrolysis. The latter point here, referring to hydrogen, is an area that continues to get coverage with some of the latter very positive about its future role and others somewhat more sceptical. Some of this scepticism is of course driven by the failure of a hydrogen economy to emerge. A notable example of such a failure has been observed in Iceland which set about achieving a hydrogen economy. However, whilst it has had limited success, it has shown that industries can be productive in the absence of fossil fuels. As an example it did have a fertiliser plant using hydrogen from electrolysis, and combined this with nitrogen to produce ammonia using hydroelectric power. As with any industry it is economics that dictate its success or failure, so whilst fossil fuels give the lowest unit cost of production then other processes are unlikely to have an impact. However, as scarcity leads to a rising price, these alternatives become more viable, and innovation is sought. A few examples below highlight some of the projects that I have encountered in my Nuffield studies.

Fertiliser from Wind Turbines

A project to convert wind energy into anhydrous ammonia fertiliser is underway at the University of Minnesota West Central Research and Outreach Center (WCROC). The project aims to provide a renewable alternative of creating the $300 million of anhydrous ammonia currently used as nitrogen fertiliser in Minnesota agriculture, all of which is derived from fossil fuel energy sources. The $3.75 million carbon-free system uses wind power from a towering turbine to produce the anhydrous ammonia, NH_3.

The system creates fertiliser by using an air separation unit to pull nitrogen from the air, while the turbine powers large electrolysers that separate water into hydrogen and oxygen. The nitrogen and hydrogen are then synthesized into anhydrous ammonia using the Haber-Bosch Process. The technology is proven; a hydrogen system model is functioning in Utsira, Norway. Using wind to power the electrolysers instead of natural gas frees a large market share and makes NH_3 production a carbon-free process that releases no greenhouse gases. The economics of this production facility all depend on the electrolysers which are very expensive and could be an impediment to future progress. Research is ongoing to look at a new process called solid-state ammonia synthesis, which could improve efficiency by bypassing the Haber-Bosch Process and the electrolyser.

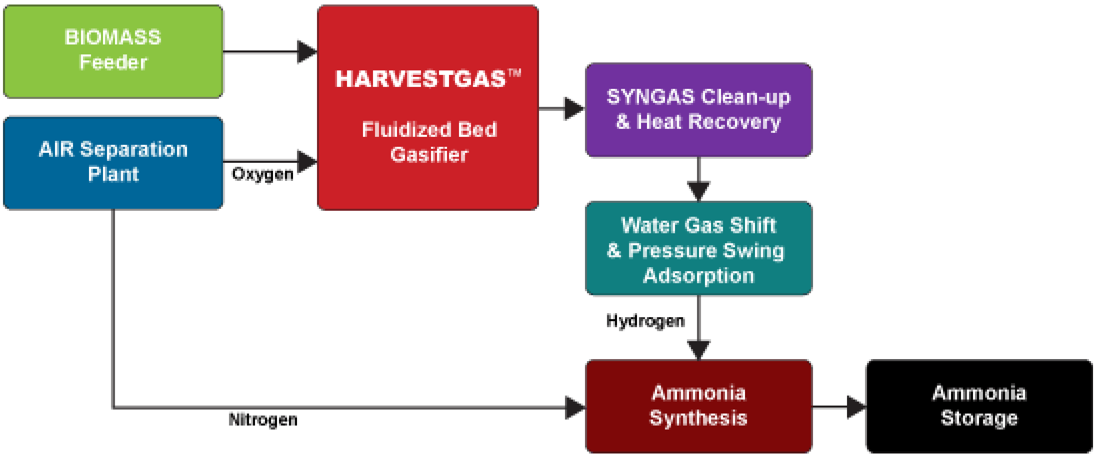


Fertiliser from Biomass

Apart from the biofertiliser that is the residue from a biodigestate unit, there are other projects exploring the ability to produce ammonia from biomass. One example is the San Francisco-based SynGest, Inc., who plan to build an $80 million facility about 40 miles west of Des Moines, Iowa, that will produce ammonia fertiliser from corn cobs. The heart of the SynGest process involves a pressurised oxygen-blown biomass gasifier designed for operation in an expanding bed fluidized mode. The HarvestGas™ system converts the biomass into a mixture of hydrogen and carbon monoxide, and is optimised to minimise the formation of methane. After the gas stream is cleaned, the carbon monoxide is "shifted" to maximise hydrogen. The hydrogen is purified and catalytically reacted with nitrogen to make ammonia. The plant includes an air separation system to provide oxygen for the gasifier and pure nitrogen for ammonia synthesis. Waste heat is recovered, thereby minimising the need for external energy supplies. Two major patents are pending.

See diagram on next page of SynGest Process

SynGest Process



BioNitrogen is an American biotechnology company specializing in the conversion of renewable agricultural waste biomass into urea fertiliser. The small-format production facilities are designed for implementation in local farm communities, close to the required feedstock. They have recently signed an Engagement Letter to raise $150 Million for a Florida plant. The funds will be used by BioNitrogen for the construction of an approximately 200,000 square foot modular manufacturing plant to transform residual agricultural waste (biomass) through a gasification process into urea, located on 40 acres of land in Hardee County, Florida. This is a very new venture with patents pending so further developments are expected in the years ahead.

Microbial fuel cells are also being investigated as a method of producing clean hydrogen that can then be combined with nitrogen to produce fertilisers. The researchers used naturally occurring bacteria in a microbial electrolysis cell with acetic acid. The bacteria consume the acetic acid and release electrons and protons creating up to 0.3 volts. When more than 0.2 volts are added from an outside source, hydrogen gas bubbles up from the liquid. This process produces 288 percent more energy in hydrogen than the electrical energy that is added to the process. Water hydrolysis, a standard method for producing hydrogen, is only 50 to 70 percent efficient.

With microbial electrolysis cells, very large farms or farm cooperatives could produce hydrogen from wood chips and then, through a common process, use the nitrogen in the air to produce ammonia or nitric acid. Both of these are used directly as fertiliser or the ammonia could be used to make ammonium nitrate, sulphate or phosphate. The researchers have filed for a patent on this work.

Nuclear Power and Fertilisers

As described earlier in the report, current nitrogen fertiliser manufacture is dominated by the use of natural gas to obtain the hydrogen to combine to nitrogen. About 96% of hydrogen, today, is made from fossil fuels: 50 % natural gas, 30 % from liquid hydrocarbons and 18 % from coal. The most current hydrogen separation processes use fossil fuels to raise the temperature and separate H2 from the natural gas.

This process releases CO2, a GHG which adds to environmental pollution. The alternative, clean, method is to use high temperature electrolysis of water. Hydrogen can be produced through the electrolysis of water in nuclear power plants. High temperature reactors are very suitable for hydrogen production, there is a lot of effort in major countries towards this goal, such as in the U.S., Canada, Japan, China and France, with major breakthroughs predicted for the future. High temperature reactors can not only produce hydrogen, but electricity as well, to meet several needs at once. Each nuclear plant produces the heat, steam and electricity for electrolysis; the breaking down of water into hydrogen and oxygen.

Section A. Summary

This opening section to my report has covered the subject underpinning the manufacture of fertiliser, that of the high use of energy that is involved in the process. However, it has revealed that in relative terms the energy consumed is low (1.1% of global energy) in comparison to the calorific value that it generates through global food production.

The concept of Peak Energy occupies many minds, but so far predictions have been found wanting and fossil fuel exhaustion looks to be a very long term issue. With continued new discoveries of shale gas then the feedstock for nitrogen production will not in the short to medium term determine the future of manufactured nitrogen. It has also demonstrated that there are already examples of alternative, renewable energy manufacturing methods that if required could be commercialized. However the unit cost of production is the bottleneck to their uptake.

Clearly there is much room for improvement in terms of the Nitrogen Use Efficiency which globally is estimated to be still around 33%. This renders 67% of the reactive nitrogen uncontrolled in the environment giving rise to pollution issues such as eutrophication, acid rain and GHGs. it is most likely to be the environmental cost that determines the future of nitrogen use and manufacture.

I will leave the final say in this section to two individuals who capture these thoughts well.

Firstly, Klaus Lackner (a professor in the Department of Earth and Environmental Engineering at Columbia University) stated that "*Technology in general and energy at its base ultimately define the carrying capacity of the Earth for humans*".

Secondly, an internet blogger on this subject (JD) "*Fossil fuels will not always be used to make nitrates - they are becoming expensive and less abundant - and another chapter will close in the long story of nitrates. The story will continue as it has in the past with new sources and methods, many of which are understood already but aren't competitive with cheaper fossil fuels . . . yet. The details are unpredictable but it's a good bet that someone like Kristian Birkeland will patent a new winning process that will serve for a time".*

Section B. Reducing the reliance on manufactured nitrogen fertiliser

In this chapter of my Nuffield report I seek to document the areas that farming can focus on in order to reduce their reliance on manufactured nitrogen. The rationale behind having this as part of a farming policy is twofold. Firstly having alternative sources of nutrient spreads risk, putting your business in a more flexible and reactive state to respond to external pressures whether they be economic, environmental or legislative, and secondly such a mindset helps to drive efficiency by adopting all technologies that can improve the use of the manufactured fertiliser that is applied. This chapter therefore focuses on the four subject areas:

1. Alternative to manufactured nitrogen.
2. Improving nitrogen recovery by plants.
3. Improving the nitrogen recommendation.
4. Nitrogen fixation by plants.

In completing this area of my study I travelled to various locations in the UK, Canada, US and Mexico all of which proved extremely valuable in compiling this chapter.

Alternatives to manufactured nitrogen

One obvious consideration as to the need for an alternative is : why replace it at all? This is of course an option, but with it comes the inevitable constraint on crop yield. This is simply a mathematical consequence as all plant dry matter contains nitrogen. Examples are wheat grain at 2% N, winter wheat leaves at 4%N and tomato leaves at 5%N. The amount of growth therefore at any given time that the soil can support will depend on the ability of that soil to deliver this nitrogen via the root system. The amount of available nitrogen will be a function of the soil's properties i.e. soil organic matter levels, organic nitrogen content, clay, sand and silt fraction, microbial content. In addition to the total amount that the plants will experience, there is then the plants' ability to take up this nitrogen. The latter is a function of the soil physical properties (e.g. clay, silt, sand fraction, compaction, soil depth) which give it its structure and determines the plant's rooting capacity. A well structured deep soil will lead to a large root mass and therefore a highly efficient system for nutrient recovery. If no supplementation of nitrogen is made then as crops are harvested a gradual erosion of soil nitrogen content occurs, further reducing the yield carrying capacity of the land. The most notorious example of this is the long term nutrient study at Rothamsted Research Centre (see below). The yields on the area that have been cropped since the start of the experiment in 1843 with no further nutrient additions demonstrate nutrient exhaustion well. At 0.82 t/ha the yields are only 9% of the fertilised area that yielded 9.54 t/ha in 2012.

Nuffield Study Visit - Rothamsted Research Station's Classical Experiments – Broadbalk

Soon after John Lawes started his collaboration with Henry Gilbert, they began a series of field experiments to examine the effects of inorganic fertilisers and organic manures on the nutrition and yield of a number of important crops. Seven of the experiments that were started in the middle of the 19th century are still going today. Most of them have undergone changes to maintain their scientific and agricultural relevance but they retain many of the original treatments and have an unbroken history that extends over more than 150 years. These experiments are a valuable resource and are used for a wide variety of scientific observations. Soil and crop samples from the experiments are added to the Rothamsted archive every year.

Harvesting Broadbalk

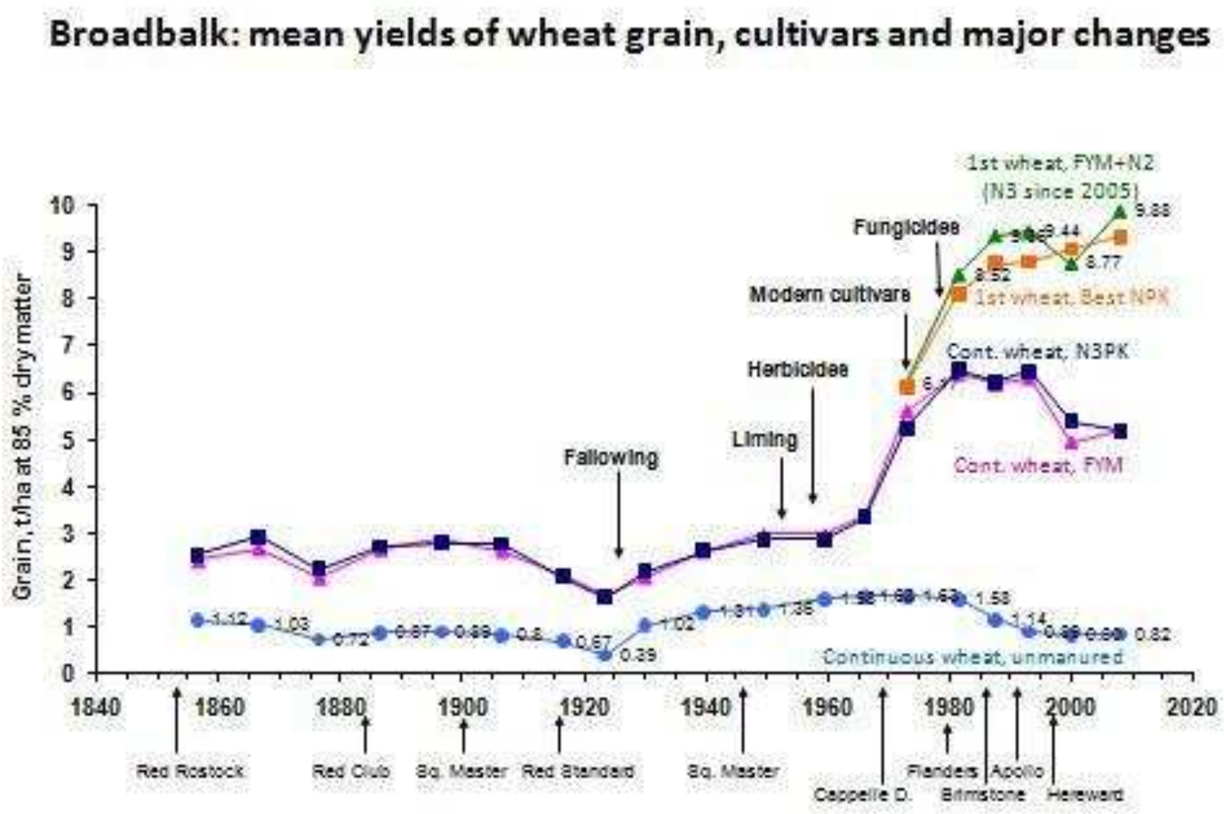
The Broadbalk experiment had its first winter-wheat crop sown in autumn 1843, and this crop has been sown and harvested on all, or part, of the field every year since then. The experiment tests the effects of various combinations of inorganic fertiliser (supplying the elements N, P, K, Na and Mg) and farmyard manure on the yield of wheat: a control strip has received no fertiliser or manure since 1843. Originally the weeds were controlled by hand weeding but later by periodically bare-fallowing and cultivating different parts of the field in different years.

From the mid-1950s, herbicides have been used but they are withheld from one part of the field. Two major modifications were made from 1968. One was the introduction of modern, short-strawed cultivars. The second saw crops other than wheat being grown on the experiment, so that yields of wheat grown continuously could be compared to those of wheat grown in rotation.

To accommodate this change, the experiment was divided into 10 sections; four continued in wheat whilst six were used to compare two 3-course rotations. There have since been further modifications and we now have:

- two sections growing continuous winter wheat
- one section growing continuous winter wheat where the straw is chopped and incorporated into the soil (on other sections, the wheat straw is baled and removed)
- one section in continuous winter wheat where no herbicides have ever been applied (on other sections, herbicides are applied routinely)
- one section in continuous winter wheat where since 1985 the use of pesticides has been restricted
- and five sections testing the rotation oats, forage maize, wheat, wheat, wheat

Lawes and Gilbert installed a tile drain under each treatment strip and used these to collect and measure the nutrients in the water that leached through the soil into the drains. After 150 years, many of these drains had collapsed and in 1993 one section was re-drained so that water leaching through the soil could again be collected and analysed.



Simply farming without supplementing soils with nutrients is clearly not an option, so alternative methods have to be used. The options fall into one of several categories:

- Using organic materials
  - Livestock/Livestock manure
  - Biodigestate
  - Compost
- Crop Rotation
- Green manures

Use of Organic Materials

Livestock / Livestock manure

Prior to the Eyde/Birkland process (1905) or Haber:Bosch (1913), farmers had no alternative but to have organic material as the central component of their soil fertility management. This of course involved having a more mixed farming enterprise with the inclusion of livestock and subsequent manure production that could be used a fertiliser for the crops. Over the years, and as fertiliser became an economic substitute, farms have become more specialised and in the loosest definition fall more into an arable or into a livestock enterprise. Livestock areas have inevitably become more focused in the areas where topography and rainfall limit choices. This migration of livestock has clearly led to a reduction in organic manure availability in those areas that no longer have them. The National Statistics demonstrate how the concentration of livestock has changed over the last century.

A comparison of livestock distribution in Engand, 1905-2005.

Year	1905				2005				
Region	Total Pigs	% of National Herd	Total Cattle	% of National Herd	Total Pigs	% of National Herd	Total Cattle	% of National Herd	% of 1905 herd
Norfolk	101,765	5%	138,319	3%	515,988	13%	87,819	2%	63%
Suffolk	149,344	7%	74,888	1%	455,525	12%	40,373	1%	54%
Cambridge	51,536	2%	58,044	1%	30,936	1%	23,865	0.4%	41%
Devon	96,124	5%	293,593	6%	95,527	2%	567,551	10%	193%
Cornwall	98,758	5%	219,451	4%	37,477	1%	340,685	6%	155%
Yorkshire	204,253	10%	548,758	11%	1,264,087	32%	569,391	10%	104%
Lincoln	109,096	5%	254,575	5%	178,948	5%	87,874	2%	35%
England	**2,083,226**	**100%**	**5,020,936**	**100%**	**3,959,480**	**100%**	**5,527,147**	**100%**	**110%**

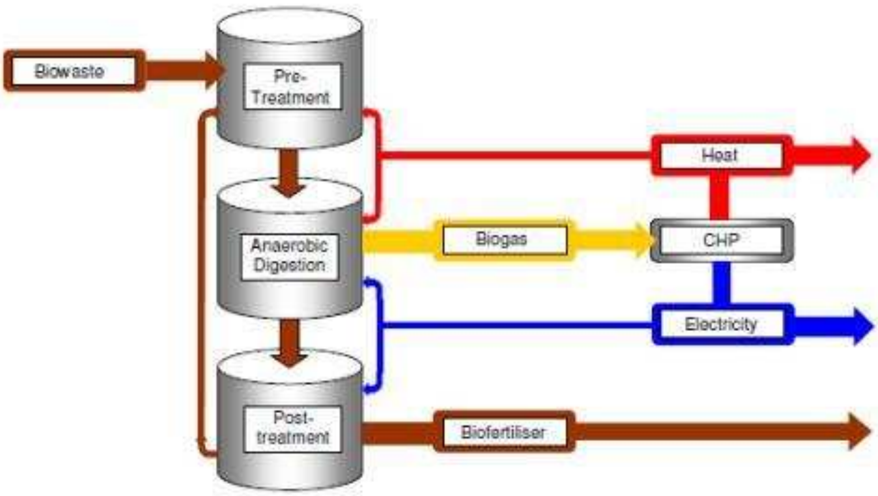
Source: Defra National Statistics County results 1905-2005

Typically the number of livestock in the eastern counties in 2005 was half the figure in 1905, this in addition to the fact that the national herd size has increased by 10%. Taking Cambridge as an example, one of the largest cereal growing areas in the UK, it had 58,044 cattle in 1905 compared to the 23,865 documented in 2005. Having livestock on a farm gives improved nutrient cycling thus one area to help reduce reliance on fertiliser is to return to using livestock as the 'nitrogen fertiliser factory'. Examples of this are happening in East Anglia and Lincolnshire with pigs being introduced on a Bed & Breakfast basis. In such examples the Pig Management is carried by one farmer, whilst the host farmer supplies the accommodation in return for the slurry/manure.

Whilst these possibilities exist, there are constraints as to their uptake. Firstly a vast increase in livestock in the east of the UK, without a subsequent reduction in the west, leads to oversupply and a poor economic return. Secondly slurry/manure comes with other nutrients which could then be returned to land that already has a plentiful supply. If such an approach is viewed in the light of a policy of replacing purchased manufactured nitrogen currently applied to the wheat and oilseed crops in East Anglia then this would require a further 1.2 million cows – increasing the herd size by 80%! Clearly a large scale return to livestock as the fertiliser supplier would serve to destabilize the demand versus supply equation. However, farmers should seek to assess their options and review whether this would be one area that could mitigate the reliance on nitrogen fertiliser.

Biodigestate

Biodigestate, or biofertiliser as it is sometimes referred to, is one of the products resulting from the Anaerobic Digestion (AD) process. This process is a natural process of converting organic matter such as household food and garden waste, farm slurry, waste from food processing plants and supermarkets, into energy. The main products resulting from AD are biogas (a mixture of methane and carbon dioxide), which is very similar to natural gas, and digestate, a low level fertiliser. The biogas can be used to generate electricity, gas or heat, or compressed for use as a biofuel. The residue, being rich in nitrates and phosphates, can be used as a fertiliser. The water industry has been using anaerobic digestion to convert effluent into energy and fertiliser for a number of years. AD is the process where plant and animal material (often described as the biomass) is converted into useful products by micro-organisms in the absence of oxygen. The biomass is put inside sealed tanks and the naturally occurring micro-organisms digest it, releasing methane that can be used to provide heat and power. This means AD can help reduce fossil fuel use and reduce greenhouse gas emissions. AD has been used in the UK since the 1800s – however with the emphasis on recycling and avoidance of land fill use, there are a growing number of AD plants in the UK processing our waste and producing green energy.



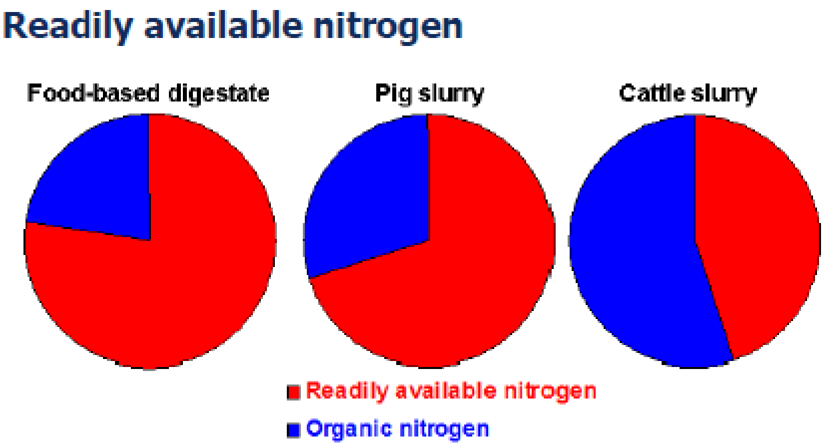
Almost any biomass can be processed in AD and converted into renewable energy: food waste, crops, slurry, crop residues, etc. AD plants can accept waste from homes, supermarkets, industry and farms, so less waste goes to landfill. However, woody biomass cannot yet be used in AD because the micro-organisms can't breakdown the lignin.

The exacted nutrient value of digest or compost will vary depending on the biomass being used. However as an example the table below highlights the values given in The Fertiliser Manual (RB209) which is the average of 15 digestates.

	Nitrogen (N)(kg/t)		Phosphate (P_2O_5) (kg/t)		Potash (K_2O) (kg/t)	
	Total	Readily Available	Total	Crop Available	Total	Crop Available
Whole Digestate	5.0 *(3.5 - 6.0)*	4.0 (80%)	0.5 *(0.25 -1.5)*	0.25	2.0 *(1.5 - 2.5)*	1.6
Green Compost⁺	7.5	<0.2 (<2%)	3.0	1.5	5.5	4.4
Green/Food Compost⁺	11	0.6 (5%)	3.8	1.9	8.0	6.4

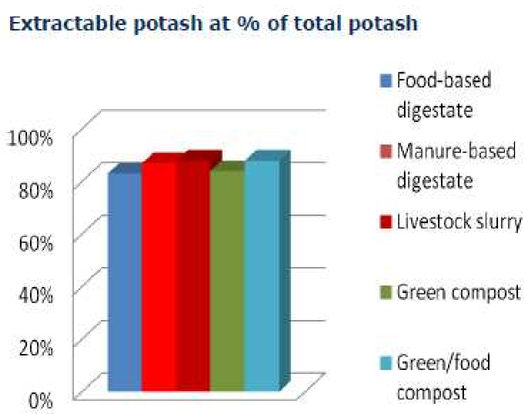
⁺ Source Defra "Fertiliser Manual (RB209)"

The other critical aspect of understanding the value of digestate as a fertiliser replacement is knowing how available the nutrients are in the product. Research trials carried out in recent years at various locations have concluded that 80% of the nitrogen is readily available, which compares very favourably with the other more traditional manures available. (See the comparison below).



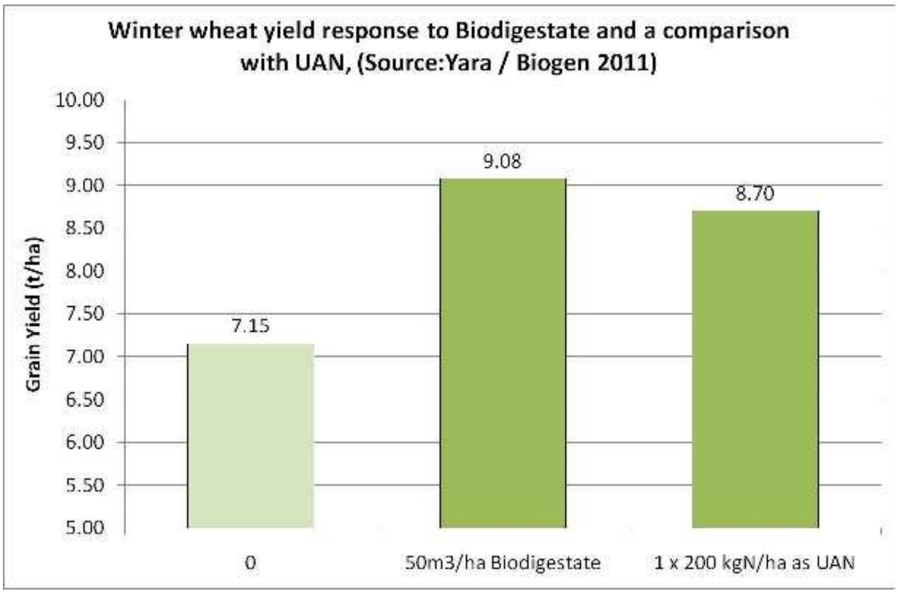
Source: The Fertiliser Manual

The digestate, as shown in the above table, also contains phosphate and potassium. Again these nutrients are in readily available forms.



Experiments conducted by the WRAP organisation, within the Digestate and Compost in Agriculture project, show that the spring application of biodigestate gives the most efficient use of nitrogen. These experiments indicated that 74% of the total N in the food-based digestate was in a mineral form that is readily available to crop plants. When this digestate was applied in spring to the potato crop the yield data indicated that 64% of the total N applied was equivalent to manufactured fertiliser N, producing yield increases in the range 11-15t/ha above the untreated control. The fertiliser N replacement value of the 30m3/ha food-based digestate application was £83/ha, based on a manufactured fertiliser N price of £1/kg.

Field trials have also been carried out with biofertiliser from the Biogen plant, Milton Ernest, Bedford. Biogen are the UK's leading operator of Anaerobic Digestion food waste plants. These trials carried out in partnership with Yara are looking to understand the full value of this nitrogen source. The 2011 results are shown below with the digestate outperforming the liquid UAN demonstrating that it can be considered as a direct replacement for manufactured nitrogen.



Nuffield Study Visit - Bedfordia Farms' utilisation of biofertiliser produced by Westwood Anaerobic Digestion (AD) plant

"We have been using biofertiliser for over six years now and are delighted with it. It is an excellent product, replacing our traditional fossil fuel based fertilisers. We utilise it in pre-planting and growing crops, and the results speak for themselves with improved yields and significant cost savings."

Ian Smith, MD Bedfordia Farms

What is Biofertiliser?
An AD plant produces renewable biogas and bio-fertiliser (also known as digestate). The biogas is used as a renewable fuel with multiple uses. It can be used in a combined heat and power unit (CHP) to generate renewable electricity and heat as is planned for the Welsh

plants, or once it has been upgraded, for use as a vehicle fuel or injection directly into the gas grid. Biofertiliser is a stabilised nutrient rich product, which is a direct replacement for fossil fuel derived fertiliser. The AD process both stabilises and sanitises biofertiliser to ensure it is safe to apply to crops. Biofertiliser contains a broad spectrum of macro and micro nutrients ideal for agricultural applications.

The nutrient analysis ranges are:

	Nutrient Content
Dry Matter	2 to 7%
Nitrogen (N)	5 to 7 kg/m3
Phosphorus (P2O5)	0.2 to 0.37 kg/ m3
Potassium (K2O)	2 to 2.5 kg/ m3

AD and Biofertiliser markets in Europe

There are many thousands of AD plants operating in the rest of Europe and in Germany alone, there are over 7,000. Virtually all of the digestate produced is recycled back into agriculture as a renewable replacement fertiliser. This is an accepted and well proven process.

Plant inputs and outputs from Westwood biogas plant

The Westwood AD plant is located in Northamptonshire. Feedstock for this plant is 49,000 tonnes of food waste per year, from which the plant can produce around 42,000 cubic metres of biofertiliser. This supplies the requirements of almost 1,000 hectares of arable land per year, growing some 10,000 tonnes of milling wheat, which is sufficient to produce 9.8million loaves of bread!

Application timing

The application timing for biofertiliser is from mid-January to the end of September if the agricultural land is located within a Nitrate Vulnerable Zone (NVZ), such as at Westwood. However the biofertiliser can be used on grassland as well as arable crops, which significantly increases the spreading opportunities beyond just a spring and summer application.

Spreading method

At Westwood, biofertiliser is spread on Bedfordia Farms land as well as land belonging to neighbouring farms. The product is transferred from the plant to the fields by two systems. The first is via a combination of underground and overland pipes which form the distribution network. Spreading is then carried out with a 24m dribble bar system attached to an umbilical cord pipe delivering up to 130cu.m per hour. The second system used for more distant fields operates with a tanker system transporting the digestate directly to a field based applicator. This machine can apply the digestate to the soil surface or directly into the soil depending on the requirements.

Application rates are typically between 25 and 50 m^3 per hectare.

Licensing and legislation

The application of biofertiliser must take account of Nitrate Vulnerable Zone (NVZ) regulations, Animal By-product regulations where appropriate, and Codes of Good Agricultural Practice for Soil, Water and Air.

There are two options to enable spreading: under a mobile deployment with the Environment Agency where the biofertiliser is still classed as a waste; or under PAS110 where the biofertiliser has to meet certain audited standards to be classed as a product. The Welsh plants will be accredited under PAS110.

Benefits to the farm
At Westwood the application of 42,000m3 of biofertiliser annually on the farm makes a significant contribution to utilised crop nutrients, supplying around 231,000kg of nitrogen, 10,000kg of phosphate, and 60,000kg of potash.

The savings in purchased crop nutrients is the equivalent of 670t of Ammonium Nitrate, 22t of triple super phosphate (TSP) and 100t of muriate of potash (MOP). At current prices this has a value of approximately £243,000. In the future as energy costs and fertiliser prices increase this is expected to be more significant. As of the 2011/12 season the digestate has halved Westwood's reliance on fertiliser.

In addition to the above input savings, there have been yield benefits of to 15% particularly in dry years where nutrient uptake is challenging.

For more information visit www.biogen.co.uk

Compost

Compost is more of a soil conditioning product than a product to replace manufactured fertiliser. However with its high levels of organic matter it has very positive effects on the soil's physical structure. Application rates for BSI PAS 100 compost will vary according to the total nitrogen content, but a typical green/food compost application at around 20t/ha (to comply with NVZ rules) will supply 5t/ha of OM. Green compost tends to have lower nitrogen contents and typically can be applied at 30t/ha. Such an effect serves to improve a plant's ability to have a large and efficient root system increasing soil nutrient recovery and hence improving nitrogen use efficiency. Nitrogen Use Efficiency (NUE) is one of the greatest variations and largely unknown components of an annual fertiliser recommendation. Improving the NUE through the use of compost will directly reduce the reliance on manufactured fertiliser.

Crop Rotation

The use of manufactured nitrogen fertiliser has enabled the arable farmer to substitute a soil fertility building rotation, with an annual 'gross margin' rotation. With the most profitable crops consistently being winter wheat and winter oilseeds, these have come to dominate the rotation at the expense of the leguminous pulses. Such a shift is borne out by the cropped areas recorded over the last 100 years. In 1905 the winter wheat area represented 16% of the arable area compared to the 45% 100 years later in 2005. This dominance has been at the expense of the rotation crops used for either stock feed or green manure. In 1905 these 'other' crops in the rotation (which included turnips, swedes, mangolds, vetches, tares, Lucerne and undersown grass) accounted for 41% of the rotation which compares to 5% in 2005. The area of pulses (peas and beans) which would represent the fertility building crop of the rotation today has changed dramatically over time. At its peak in the early 2000s there was 233,000 ha in England, representing approximately 6% of the arable area. In 2010/11 the area was 56% of this peak, with some 121,000 ha less being grown. Soils that have had a pulse crop typically contain an extra 20 kg of available N/ha. This reduction in area represents £2.42m worth of fixed nitrogen lost from the UK arable rotation. Legume crops have been shown to fix large amounts of nitrogen during the growing season: typically in the region of 100-200 kgN/ha/annum as shown in the table below which is data collated by Mark Peoples and Jill Griffiths for CSIRO Plant Industry. The amount of this fixed nitrogen that is then available for the following crop will depend on the management of the legume (i.e. harvest, desiccated, ploughed in as green manure etc.)

Estimates of the amounts of shoot nitrogen fixed by various legumes growing at different locations in south-eastern Australia, (Source, Mark Peoples and Jill Griffiths for CSIRO Plant Industry) can be *seen in the chart on the next page.*

Not only is the grower missing out on this extra nutrient value, there is potentially an overall downside to the very narrow rotations being practised on many UK farms. Recent research conducted by the NIABTAG Group has concluded that good rotations will give the greatest Gross Margin, with their conclusion putting a value of £2345/ha on a 'good' rotation versus the £1088/ha value calculated for the poor rotation. The best examples of where rotations are being used to optimise soil fertility are found in the organic sector where 'life without manufactured nitrogen' is a rule of engagement in this farming system. In recent years more research has been conducted to identify key species to have within a rotation to give specific traits e.g. fertility improvement, soil structure improvement and soil moisture retention.

Location	Legume species	Amount of shoot nitrogen (N) fixed[a] (kgN/ha/yr)	
		Range	Average
Victoria			
Horsham	Faba bean	82–174	128
	Lentil	60–110	90
	Field pea	85–166	138
	Vetch	72–160	116
	Annual medic	2–90	39
	Lucerne	19–90	43
Rutherglen	Lupin	59–244	150
	Sub-clover	99–238	160
NSW			
Junee	Field pea	133–183	160
	Sub-clover	21–118	56
	Lucerne	103–167	128
Stockinbingal/Temora	Faba bean (2002)	112–146	123
	Lupin/field pea (2008)	12–83	45
Condobolin	Lupin	26–93	51
	Field pea	35–111	58
Trangie	Lucerne	13–82	37

[a] The data set includes experimental trials and on-farm measures collected from commercial crops and pastures.

Source: Peoples *et al.* (2001) *Plant and Soil* 228: 29-41, and includes unpublished data of Cela, Angus, Swan, Crews and Peoples.

Nuffield Study Visit - Institute of Organic Training and Advice (IOTA)

Institute of Organic Training & Advice

Conference 23.02.201 at Cirencester

As part of my Nuffield Study I was delighted to be able to attend the annual conference of the Institute of Organic Training and Advice (IOTA). This event was organised by Mark Measures, IOTA Director, and reviewed the results from the Legume Link research project, using legume-based mixtures to enhance the nitrogen use efficiency and economic viability of cropping systems.

Project aims

The overall aim of the project is to improve nitrogen use efficiency in UK arable systems. It aims to create a legume based mixture (LBM) that can have significantly improved resilience in fertility building and nitrogen release dynamics compared to the traditional grass/clover mixtures, over a range of environmental conditions.

By studying the growth parameters of individual legume species, and grasses in field trials, and the mixture of all trial species (the all species mixture - ASM) in participatory trials, we will better understand the potential, and the mechanisms by which a designed LBM may increase the profitability of UK arable systems, and have robust data on which to base the development of commercial seed mixes.

Key Messages:

- Cover crops are useful tools in the rotation
- Cover crops increase infiltration
- Legume-based cover crops increase yield compared to "current" rotational system (by approximately 5%)
- This effect is consistent across a number of different crops (wheat, oil seed rape).
- As a result of this and through decreasing costs for N fertilization economic performance is improved.
- While establishment costs for cover crops may currently outweigh economic benefits, this changes with rising costs of bagged N.
- Diverse mixtures show a higher productivity than *monocultures* (biomass, crop cover).
- A more complex (functionally diverse) mixture shows a higher productivity than currently used ones (biomass).
- This advantage of the mixture increases over time
- And the advantage is higher on less fertile soils (low organic matter).
- This increased biomass is links through to higher yield of the following crop.
- Mixing species with different properties allows better weed control throughout the season.

http://organicadvice.org.uk/soil_papers/adv_leaflet.pdf

Green Manures

Green manures are generally considered to be crops grown for the benefit of the soil. They have been used in traditional agriculture for thousands of years but conventional farming systems have moved away from them over the years as fertilisers and pesticides have taken their place. Organic farmers have continued with these crops with growing sophistication as more is understood about the benefits different species give. The conventional sector should show renewed interest in this area in its need to reduce its reliance on manufactured fertiliser.

Green manures bring a number of advantages to the farming system:

- Adding organic matter to the soil
- Increasing biological activity
- Improving soil structure
- Reduction of erosion
- Increasing the supply of nutrients available to plants (particularly by adding nitrogen to the system by fixation)
- Reducing leaching losses
- Suppressing weeds
- Reducing pest and disease problems
- Providing supplementary animal forage
- Drying and warming the soil

A number of disadvantages have also been identified which do stand in the way of their uptake:

- Direct costs of seed and extra cultivations
- Lost opportunities for cash cropping
- Extra work/labour requirement
- Exacerbated pest and disease problems (due to the 'green bridge' effect)
- Potential for the green manures to become weeds in their own right

A wide range of plant species have been used as green manures, each bringing different benefits. When included in a rotation they should be treated as a crop to ensure successful establishment and growth. Typically green manures fall into distinct categories with examples as follows:

Long term green manures.
Leys are a basic part of many organic arable rotations. Where animals are present on the farm the leys would usually be grazed or cut for silage but in stockless systems they are normally cut monthly during the summer period and the mowings allowed to remain on the surface as a mulch. Such leys may be pure clover (when nitrogen fixation is a priority) or a grass/clover mixture (when organic matter build up is also important).

Winter green manures.
These are typically sown in the autumn and incorporated in the following spring. They can be a good way of fitting a fertility building crop into a rotation if they can utilise land that would otherwise be bare. However, it can be difficult to establish them early enough if harvest of the preceding summer crop is delayed. They can be legumes (eg vetch) but a major use for this class of crops (even in conventional agriculture) is to minimise nitrogen leaching; when used for this purpose they are often called winter cover crops.

Summer green manures

These are normally legumes grown to provide mid rotation fertility, especially nitrogen. They may be grown for a whole season (April to September) or for a shorter period between two cash crops. These shorter-term green manures can include non-legumes such as mustard and phacelia.

Green manures may also be used in intercropping systems. On arable farms, leys are usually established by undersowing them in the preceding cereal crop. This gives the green manure a longer growth period and can help in weed control. This has also been practised with horticultural crops but care is needed to avoid too much competition.

Many different plant species have been used in systems. However all have general characteristics that include cheapness of seed, rapid germination and growth, competitive, ability to grow in nutrient-poor soil, ease of incorporation and unlikely to become a weed. For the role of nutrient building then these are typically legumes. Nitrogen fixation will only happen in the presence of correct strains of *Rhizobium* bacteria. For more common legume species these will certainly be present naturally in the soil but some more unusual species may benefit from inoculating the seed before sowing. There are clearly many options for green manures including cereals (rye, oats) and grasses (Italian, annual (Westerwolds) and perennial). The table below represents some examples that could be introduced to reduce reliance on nitrogen fertiliser.

CLOVERS	**Suitability:**	**pH preferred**	**Height:**	**Frost tolerance**	**Comment**
White clover (Trifolium pratense)	Ley or inter-cropping	5.6-7.0	15-30cm	Good	Common in grazing leys. White clover is shallow rooted and makes little growth in dry conditions. Continued defoliation stimulates root growth and N fixation. Varieties are classified into small leaved and large leaved. Small leaved varieties maintain good ground cover under hard grazing. Large leaved varieties are more suited to light grazing and are less persistent. Medium leaved varieties have intermediate characteristics relative to large and small leaved varieties.
Red clover (Trifolium repens)	Ley or inter-cropping	6.0-7.5	15-30cm	Good	This is higher yielding and taller than white clover. Its deep taproot makes it more drought resistant than white clover. Varieties traditionally fall into early and late flowering groups. Early types produce more early spring growth with most of the yield coming from the first cut. Late varieties are more persistent and can be used in medium term leys. Typical annual yields of dry matter are 10-15 t/ha.

Crimson clover or **Italian clover** (Trifolium incarnatum)	Leys	5.5-7.0	30-60cm	Good	It is an annual and does not recover after grazing or cutting and gives lower yields than red clover.
Subterranean clover (Trifolium subterraneum)	Inter-cropping	5.5-7	20cm	Good	This is a prostrate plant with long branched creeping stems. It may be particularly suitable for intercropping. The flowers (self pollinated) are pushed into the soil; the plant then dies off but regenerates the following year (possibly causing a weed problem).
MEDICS	**Suitability:**	**pH preferred:**	**Height:**	**Frost tolerance:**	**Comment**
Lucerne or alfalfa (Medicago satvia)	Leys	>6.5	40-90cm	Good	This is a long-lived perennial plant with a deep taproot ideally suited to light and chalky soils and dry climates. Where it can grow well it is the most high yielding of the herbage legumes, producing 15 t/ha of dry matter annually. Excessive competition must be avoided particularly when young.
Trefoil, yellow trefoil, black medic or hop clover (Medicago lupulina)	Summer green manure		10-15cm	Good	This is an annual or biennial legume that can give good yields even on thin calcareous soils. Its main use is as a green manure undersown in cereals. Because it is relatively low growing it also has potential in vegetable intercropping systems
OTHER LEGUMES					
Sanfoin, St Foin, cockshead or Holy Grass (Onobrychis viciifolia).	Summer grazing or ley	>6	30-60cm	Reason-able	It needs good drainage and prefers a warm climate. It is perennial with a deep taproot and is drought resistant. It is a valuable animal feed nutritionally although yields are much lower than lucerne. Common sanfoin is truly perennial but can only be cut once a year. Giant (or double cut) sainfoin is more productive but only persists for a couple of years.

Lupins: White lupin (Lupinus albus), **bitter blue lupin** (Lupinus angustifoilus) and **yellow lupin**	Summer green manure	Tolerates acid soils	60-70cm	Poor	These were the traditional green manures of temperate climates. They are well adapted to sandy soils. The plants have deep penetrating taproots and the stems are erect yet easily crushed and readily decomposed.
Common vetch or **tares** (Vicia satvia) and **hairy vetch** (Vicia villosa	Winter Green Manure	7	50cm	Good	Winter vetch is very valuable as an autumn sown cover crop because its large seeds enable it to become established later than most other legumes and thus be fitted in after the harvest of many summer- grown crops. Pest damage (insects and birds) may be devastating in some places but where it grows well vetch can release large amounts of available N to a following crop.
Grasses					
Cocksfoot (Dactylis glomerata**)**	Winter Green Manure or Ley	6-8	60-100cm	Good	Cocksfoot is slower growing in the first year of sowing than perennial ryegrass. Cocksfoot has a reputation for producing a large amount of root mass which is beneficial for soil organic matter content and soil structure.
Timothy (Phleum pratense)	Winter Green Manure or Ley	6-7	30-50cm	Good	Timothy is well adapted to cooler wetter areas and has good winter hardiness.
Brassicas					
Mustard (Sinapis alba)	Summer or Winter Green Manure	5.3-6.8	30-60cm	Poor	This is one of the most widely grown green manures. It grows large very quickly but it is very shallow rooted. It survives in some winters. Frost kill need not be a disaster for a winter green manure, providing that it occurs late in the season and there has been time for significant nitrogen conservation to have occurred. Much interest has been shown in caliente type varieties recently. These have been bred for their high glucosinilate content that under the right conditions can have biocidal properties against pests, weeds and diseases.

NON LEGUMES	**Suitability:**	**pH preferred:**	**Height:**	**Frost tolerance:**	**Comment**
Phacelia (Phacelia tanacetifolia	Summer or Winter Green Manure		30-60cm	Poor	This grows rapidly from winter or spring sowings. Not completely frost hardy but may survive in mild winters. Can become a weed in subsequent crops.
Buckwheat (Fagopyrum esculentum)	Summer Green Manure	5-7	40-60cm	Poor	This is a broad leaved summer annual that requires only a short growing season (2-3 months). It may self seed to produce a second crop – this may cause a weed problem. It will tolerate infertile soils but performs badly on heavy soils. It is believed to be effective at scavenging the soil for phosphorus. May have some effective on weed germination.
Chicory (Chichorum intybus)	Summer or Winter Green Manure	6-8	40-100cm	Good	It can have beneficial effects on soil structure, producing a large taproot which can break through plough pans. It is good for grazing, containing high levels of calcium, potassium and other micronutrients. Chicory can be sown in autumn or spring. It is important that reproductive growth is cut to prevent an abundance of unpalatable woody material forming.

Source:A guide to sowing and management of green manures

Crop	Seed rate (kg/ha)	Sowing time	Can be mown or grazed?	Duration
White clover	10-15	Mar-Aug	Yes	2-5 years
Red clover	15-20	Mar–Aug	Yes	1-2 years
Crimson clover	15-18	Mar-Jun, Aug	No	2-3 months
Sub clover	10-15	Mar-Jun, Aug	Yes	5-7 months
Lucerne	20–25	Mar-Jun, Aug	Yes	1-3 years
Trefoil	10-15	Mar-Aug	Yes	Up to 1 year
Lupins	200-250	Mar-May	No	3-5 months
Field beans	200-250	Mar or Oct	No	5-7 months
Winter vetch	75-125	Mar-Sep	Not generally	3-6 months
Grazing rye	150-180	Aug-Oct	Yes	7 months
Mustard	8-12	Mar-Sep	No	2-3 months *
Stubble turnips	8-10	Apr-Aug	Yes	8 months
Phacelia	10-15	Apr–Jul, Sep	No	2–3 months*
Buckwheat	60-80	Apr-Aug	Yes (if done early)	2-3 months
Westerwolds ryegrass	32–38	Mar-Jun, Aug	Yes	9-12 months
Chicory	12-18	Apr-Aug	Yes	12-18 months

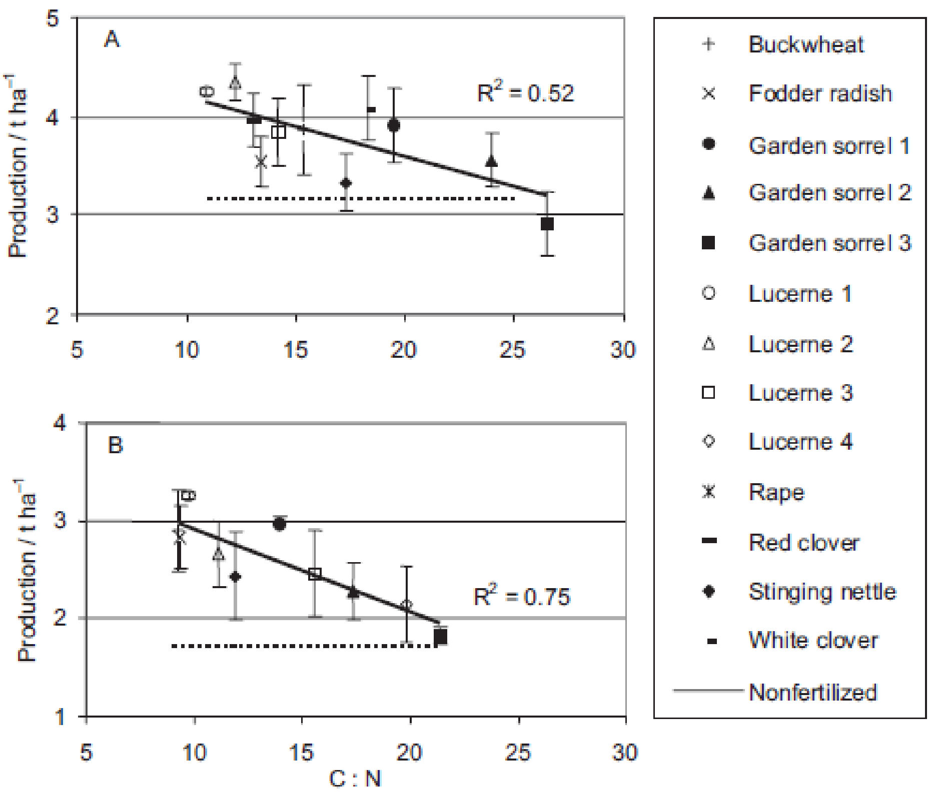
* this depends on the time of sowing – longer if overwintered

Source: GREEN MANURES, A review conducted by HDRA as part of HDC Project FV 299:

Green manures do represent an opportunity to improve nutrient cycling/recovery from soils. In addition some have properties that may help in reducing weed germination. Nitrogen and phosphate recovery by these plants can be very high. An example being overwintered vetch that can accumulate up to 200kg N/ha by early May. The availability of the recovered nutrient that resides in the biomass will vary according to the species, technique used to incorporate and succulent nature of the crop. The woodier the material, the longer it will take to decay and the nutrient release will be slower.

Mobile Green Manures

Another more novel use of green manures can be found in the horticultural sector in Denmark. At the Danish Centre for Food and Agriculture, Aarhus University, research is ongoing in the area of 'mobile green manures'. The concept of this has been developed as an alternative fertiliser that can replace organic manures from non-organic farms which is currently being used by organic farmers. This use of 'non organic', organic manures is being gradually phased out so the demand for alternative fertilisers is going to steadily increase. It is currently focused on vegetable production as opposed to large areas of broad acre crops. The approach is to grow a green manure crop on an area of land and then harvest this in a state that gives maximum nutrient availability. This harvested crop can be ensiled, dried, pelleted etc to get it into a condition suitable for spreading as a fertiliser onto another crop e.g. cauliflower, leeks etc. The harvest time is critical in terms of creating plant residue that contains available nitrogen. Plant available nitrogen is optimised by producing green manure with a low C:N ratio. During the decomposition process microbes breakdown the green material using carbon as the energy source and nitrogen for building cell structure. If the carbon supply limits microbial activity, this allows the plant to take up the available nitrogen as opposed to the microbes, resulting in greater productivity from the crop. Jorn Nygaard Sorensen and Kristian Thorup-Kristensen have demonstrated in their work that moving a Lucerne mobile green manure crop from a C:N ratio of 10 to 20 through late harvesting resulted in a 34% reduction in yield from the kale it was applied to.



Dry matter at harvest of (A) cauliflower and (B) kale leaves in relation to C : N ratios of applied green manure (160 kg total N ha–1). Garden sorrel and lucerne were harvested at three or four different developmental stages. The dotted line represents the dry-matter production of nonfertilized plants. Bars indicate ± SE. Field experiments in 2006 and 2007 (Experiment 2).

The investigation also looked at the recovery of nutrients following this method of fertilisation. The nitrogen recovery is a critical element in improving Nitrogen Use Efficiency in farming systems and was measured by calculating the net accumulation of nitrogen (treated minus control) and converting this to a fraction of that nitrogen applied as the mobile green manure (160kgN/ha). The results in the table below give the N recovery figures which go from -1% (Garden sorrel 3) to 39% (Lucerne 2). This figure does not compare very favourably with typical inorganic nitrogen fertiliser recovery which globally is at approximately 33%, and in Europe approximately 60%. Clearly 69-100% of the 160 kgN/ha of green mobile fertiliser is in a reactive state and thus has potential to impact on its surrounding environment (leaching, volatilisation etc). The most important aspect of these mobile green manures is where they were grown in order to accumulate the nutrients held within them to be recycled into another farming system.

Green manure	N accumulation /kg ha^{-1}	N recovery	N / g kg^{-1}	P / g kg^{-1}	K / g kg^{-1}	S / g kg^{-1}
None	92 ± 16		30 ± 1	3.5 ± 0.2	24 ± 2	12.6 ± 0.5
Buckwheat	120 ± 17	0.18 ± 0.12	32 ± 2	4.6 ± 0.1	34 ± 2	12.3 ± 0.7
Garden sorrel 1	126 ± 15	0.21 ± 0.11	34 ± 2	4.8 ± 0.4	32 ± 2	12.1 ± 0.7
Garden sorrel 2	107 ± 10	0.09 ± 0.07	31 ± 1	4.4 ± 0.4	30 ± 3	12.2 ± 0.0
Garden sorrel 3	91 ± 9	−0.01 ± 0.06	33 ± 1	4.3 ± 0.3	26 ± 3	11.6 ± 0.3
Lucerne 1	142 ± 3	0.31 ± 0.10	36 ± 1	3.8 ± 0.2	29 ± 2	12.4 ± 0.3
Lucerne 2	155 ± 6	0.39 ± 0.13	37 ± 1	3.9 ± 0.2	34 ± 3	11.7 ± 0.1
Lucerne 3	127 ± 12	0.22 ± 0.04	36 ± 2	3.8 ± 0.3	29 ± 2	11.7 ± 0.3
Rape	106 ± 10	0.08 ± 0.13	31 ± 1	3.8 ± 0.3	23 ± 2	12.8 ± 0.2
Red clover	136 ± 19	0.27 ± 0.02	35 ± 2	3.8 ± 0.3	30 ± 1	11.6 ± 0.7
Stinging nettle	102 ± 4	0.06 ± 0.08	32 ± 2	4.0 ± 0.5	27 ± 5	12.0 ± 0.4
White clover	129 ± 12	0.23 ± 0.03	36 ± 3	4.0 ± 0.3	31 ± 2	11.5 ± 0.6
Significance[a]	**	**	ns	ns	ns	ns
LSD	31	0.19	–	–	–	–

[a] Significance level: ns, not significant; $^{**}p \leq 1\%$

Green-manure effects (160 kg total N ha–1) on the N accumulation and apparent N recovery by aboveground cauliflower plants, and on the nutrient concentration in the dry matter of cauliflower leaves. The results are means of three replicates ± standards errors.
Field experiment in 2006 (Experiment 2).

Their work has also explored how different species accumulate different nutrients. Distinct groups were identified which had higher levels of Boron, Sulphur, Phosphate and Potassium. Such differences could be exploited to replace specific inorganic fertiliser applications. They went on in their studies to calculate how much area of a crop would be needed to be grown to supply 1000 kg N, which is equivalent approximately to three tonnes of a 34.5% ammonium nitrate.

See a second chart on next page

Harvest date, nutrient concentrations in shoot dry matter, C : N ratio, biomass-dry-matter production, and the growing area required to produce 1000 kg N. Numbers following red clover, white clover, lucerne, and garden sorrel denote increasing plant age with 2 weeks between each harvest (Experiment 2).

		Harvest date	N / g kg−1	P / g kg−1	K / g kg−1	S / g kg−1	C : N	Biomass / t ha−1	Area / ha t−1
2005	buckwheat	20 Jun	27	4.3	39	2.1	15	2.4	15
	lucerne	10 Jun	32	2.7	21	2.1	14	1.1	28
	phacelia	21 Jun	19	3.6	38	1.5	21	4.3	12
	rape	11 May	26	4.5	19	2.7	16	2.7	14
	red clover 1	19 May	39	2.3	17	2.3	11	0.7	37
	red clover 2	1 Jun	35	3.0	33	2.0	12	2.8	10
	red clover 3	14 Jun	27	2.5	25	1.5	16	4.3	9
	stinging nettle	17 Jun	22	4.1	23	2.5	19	4.3	11
	white clover 1	19 May	37	3.6	31	2.3	11	1.0	27
	white clover 2	1 Jun	25	3.2	26	1.7	17	3.3	12
2006	buckwheat	6 Jul	27	2.9	38	1.6	15	2.4	15
	garden sorrel 1	9 Jun	22	3.9	26	1.2	19	2.1	23
	garden sorrel 2	21 Jun	17	3.5	32	1.0	24	2.7	21
	garden sorrel 3	6 Jul	16	3.3	29	0.9	26	3.3	19
	lucerne 1	23 May	40	3.1	26	1.8	11	2.2	12
	lucerne 2	7 Jun	36	2.7	23	1.6	12	3.2	9
	lucerne 3	21 Jun	30	2.2	16	1.7	15	4.6	7
	rape	26 May	32	4.2	20	6.1	13	1.3	23
	red clover	9 Jun	33	2.7	28	1.2	13	4.1	7
	stinging nettle	16 Jun	24	3.1	18	1.7	17	4.1	10
	white clover	9 Jun	23	2.7	25	1.0	18	2.8	15
2007	buckwheat	31 May	41	5.0	48	3.1	9	2.3	11
	fodder radish	20 Jun	41	8.3	51	6.5	9	5.6	4
	garden sorrel 1	9 May	30	3.9	25	3.0	14	2.3	14
	garden sorrel 2	23 May	24	3.8	32	2.4	17	4.0	11
	garden sorrel 3	13 Jun	20	3.0	21	2.3	21	5.8	9
	lucerne 1	9 May	44	4.1	28	3.0	10	2.9	8
	lucerne 2	23 May	39	2.5	22	3.1	11	4.7	6
	lucerne 3	6 Jun	28	2.3	23	2.2	16	7.0	5
	lucerne 4	20 Jun	22	2.3	18	2.6	20	4.5	10
	stinging nettle	30 May	33	3.9	29	5.9	12	4.6	7

Nuffield Study - Plant-based fertilisers for organic vegetable production

Jorn Nygaard Sorensen - Conclusions

'The results obtained from these experiments confirm our hypothesis that it is possible to produce mobile green manures with high concentrations of nutrients, but low in C. Garden sorrel, dyer's wood, rape, and fodder radish represent species with high P concentrations, and cruciferous crops such as dyer's wood, fodder radish, and rape showed high S concentrations. Dyer's wood, salad burnet, dandelion, and stinging nettle showed high concentrations of B, whereas species such as dandelion, chicory, dyer's wood, and garden sorrel showed high concentrations of K. Low C : N ratio could be obtained by harvesting at

early growth stages. Low C : N ratio was, in general, obtained when the leaf-to-stem ratio of the green manure plants was high. Further, green manures with high nutrient concentrations and low C : N ratios have great impact on their value as fertiliser in vegetable production.'

Plant-based manure such as pelletized lucerne, which has been used in relation to leek, belongs to the future. From 2015 the use of non-organic animal manure will gradually be phased out in organic farming, an area in need of alternative manure types. Scientists from Aarhus University are currently studying ways in which to achieve a maximum production of organic nitrogen by using green manure and at the same time to ensure that the manure quality is optimised.

The manure of the future does not originate from animals but from plants. Green manure is the way ahead at a time when the use of non-organic animal manure in organic farming is going to be phased out. The use of non-organic animal manure in organic farming will soon be a thing of the past. In the near future this will be replaced by green manure – in other words, a plant-based manure. In a new project at Aarhus University scientists will therefore look at how to get the maximum benefit of nitrogen in green manure while optimising the quality of the fertiliser. The objective is to optimise the yield of the nitrogen in plant-based fertiliser that is stable and readily available when needed, says senior scientist Jørn Nygaard Sørensen, who is behind the project.

The background for the project is that the current use of non-organic animal manure in organic farming will gradually be phased out from 2015. Organic farms therefore need alternative sources of fertiliser. There is also an ambition to increase the use of green manure to avoid contamination with animal manure, which represents a potential health risk.

Green manure quality

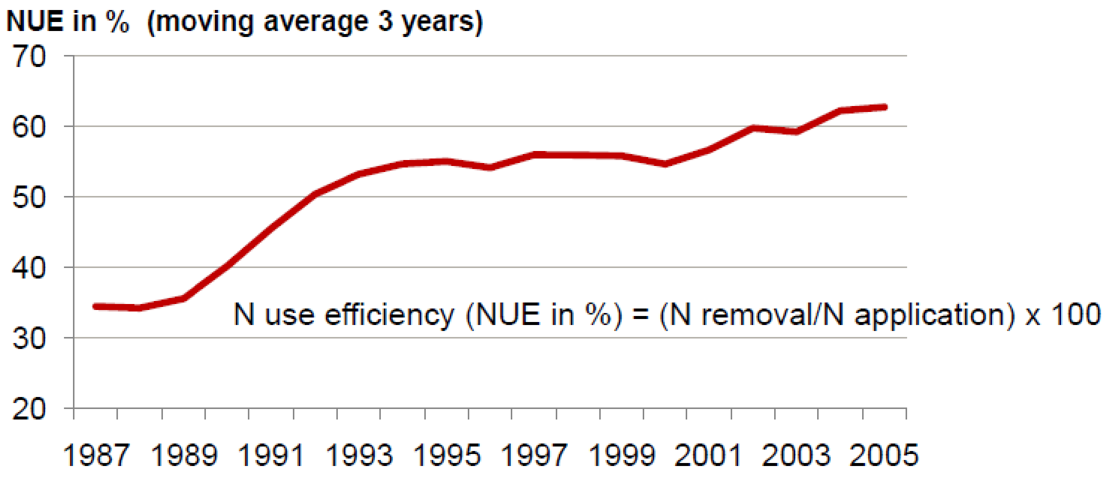
Previous studies of green manure have shown that it is not just a question of producing a high nitrogen yield per hectare, but that the quality of the green manure is also very important. The quality depends on the carbon/nitrogen (C/N) ratio of the manure.

- *If the C/N ratio is too high, the nutrients will be released too slowly for the cash crop to get full benefit of them',* explains Jørn Nygaard Sørensen.

To achieve the highest yield when used on cash crops it is therefore important that the C/N ratio in the green manure crops is low. A low ratio is achieved by harvesting the green manure crops at an early growth stage, because the later the plants are harvested, the higher the C/N ratio. The challenge for the scientists is to find not only suitable plants with a potentially high nitrogen content but also the optimum harvesting time for the green manures when the nitrogen content is high and the C/N ratio low. When producing mobile green manures the optimum harvesting time will be a balance between the amount of nitrogen produced per hectare and the C/N ratio of the biomass. The nitrogen yield per hectare is also a balance between the quantity of biomass produced and the nitrogen content. In this way the nitrogen yield can be maximised and the quality optimised, concludes Jørn Nygaard Sørensen.

Improving nitrogen recovery by plants

In 1999 Raun and Johnson stated the Nitrogen Use Efficiency (NUE) for global cereal production to be 33%. In the UK the Fertiliser Manual (RB209) states that typical nitrogen use efficiency for cereals is between 55 and 70% depending on the soil type. Calculating the Nitrogen Use Efficiency from a collection of UK nitrogen dose response experiments, and assuming at the nitrogen optima the grain Nitrogen is 2%, a typical value is 40%. Yara ASA has also quoted the improvement in NUE across Europe over the last twenty years (see below).



Source: own calculation based on FAO and Efma data

All these datasets demonstrate that there is still much room for improvement in NUE and with such an improvement comes a reduced reliance on manufactured nitrogen. The areas that are most likely to help realise this improvement involve plant genetics, developing a more accurate approach to the nitrogen recommendation and improving the rooting environment i.e. soil structure. There are developments in all these areas that can be summarised as follows:

Genetic Management

In 1946 it was discovered that gene flow occurred naturally between species, e.g. bacteria to bacteria, or plant to plant. This is how natural resistance has developed; either to antibiotics or herbicides; and how evolution brings about species with new traits, or traits are lost through being redundant. This process gives rise to the genetic variation we see across species and has been used throughout plant breeding history to produce new varieties that have beneficial characteristics. A classic example of how a plant's genetic makeup has changed over time is the wheat plant. Wheat is believed to have been first domesticated around 9000 BC in the region of southeast Turkey. It was called Einkorn (*T. monococcum*) and genetically is described as a diploid, containing two sets of chromosomes.

Einkorn - Triticum monococcum

Triticum dicoccum

Triticum aestivum

9000BC 'Genetic Modification in nature'

At a similar time Emmer wheat (*Triticum dicoccum*) was being domesticated. This was a further genetic development as Emmer was a natural hybridization between two wild grasses - *Triticum urartu* (closely related to wild einkorn (*T. boeoticum*), and an *Aegilops* species. Both of these were diploids which meant that this new wheat was now a tetraploid, i.e. it had four sets of chromosomes. Durum wheat is also a tetraploid and developed through a natural hybridisation just as Emmer wheat did. Farmers continued to make selections from their fields of wheats that showed favourable traits – ease of harvest, yield etc.

10-12000 years ago new wheats started to dominate. Spelt and Common bread wheat were now the favoured types. These two were again the result of a natural hybridisation between Emmer wheat and the wild goat-grass Aegilops tauschii. This hybridisation took the tetraploid to an hexaploid, now containing six sets of chromosomes (i.e. 42 chromosomes), somewhat different to the 14 in the original species.

This 'natural' genetic modification, whilst being highly successful, has taken rather a long time so biotechnology is exploring the ways that genetic management can be done faster and more efficiently with very targeted genetic manipulation. In the summer of 2010 BBSRC funded scientists released the first draft wheat genome sequence. It is 5 times larger than the human genome and each plant has three genomes. Once fully sequenced genetic variations with the desired traits can be produced more quickly. In terms of desired traits for improved nutrient recovery then the following are examples to be explored:

- Root biomass and architecture that could be expected to give improved soil nutrient exploration.
- Improved remobilisation of stored stem carbohydrate.
- Improved photosynthetic efficiency by either leaves or spikelets.

There are various institutes across the world working on the genetic improvements that could be made. As part of my Nuffield Study I visited some of those leading the way in this field including CYMMIT, Arcadia, John Innes and University of Alberta. Whilst all these are working on the genetic improvements that could bring improved NUE, each has different approaches.

Nuffield Study Visit – CIMMYT

CIMMYT is the International Maize and Wheat Improvement Centre, and the home of Dr Norman E. Borlaug. Its basic aim is to improve the yields of maize and wheat through genetic selection and improved agronomy. With over 300,000 experimental plots, CIMMYT is continually looking at improving the wheat plant by exploiting its current genetic base, or introducing new genetic traits.

One of their areas of agronomic research is to improve the Nitrogen Use Efficiency (NUE) of this crop. Within this research program they are looking to achieve this through a number of ways. One of these is to look at the wild relatives of wheat and see if any of these express improved NUE traits that could then be bred back into modern day varieties. This program is still in its early days so as yet no results/findings have been reported.

Plots of wild relatives of wheat at CIMMYT

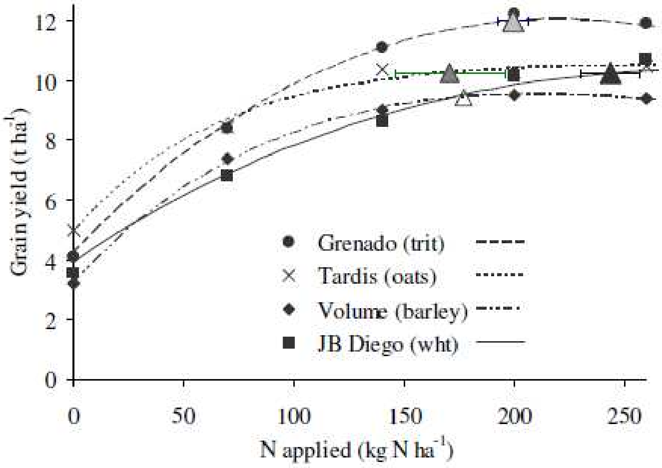
CIMMYT – Synthetic Wheat

Another technique being utilised at CIMMYT is to recreate the crossing that happened thousands of years ago when wheat hybridised to become a hexaploid. It is hoped that this will further diversify the genetic base bringing new traits to help improve performance through resistance to drought, waterlogging and/or disease. The term used is 'Synthetic Wheat' and, with now over 1000 new 'lines' from which to make selections, progress is being made. One example of a trait being assessed is the 'stay green' trait whereby the plant's photosynthetic capacity is retained for longer. It is hoped that some of the new lines being screened will show improvements in Nitrogen Use Efficiency.

A field of Synthetic Wheat plots at CIMMYT's El Batan experimental station

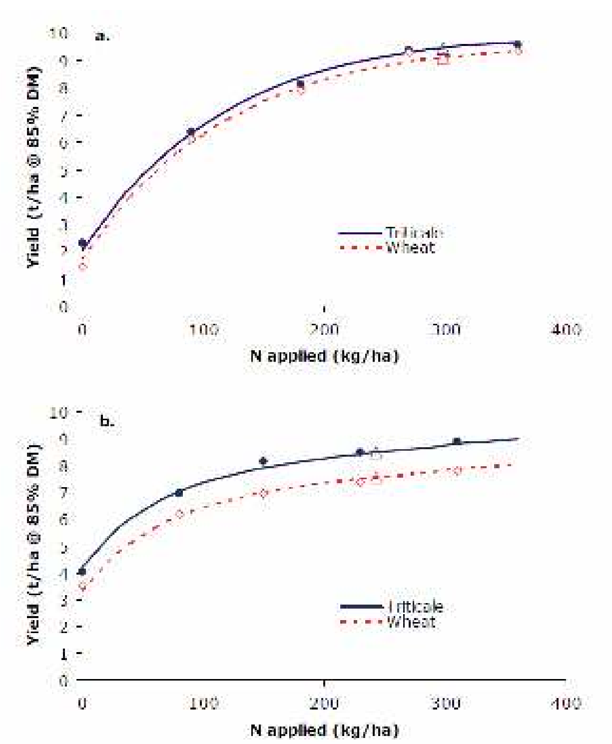
Triticale and improved NUE

There is evidence from UK data that there is genetic variation with regards to nitrogen recovery within the cereal group. ADAS data from 2009 experiments confirms this within which triticale and oats gave higher yields where no nitrogen fertiliser was used, and also when nitrogen was applied Triticale gave 2t/ha more grain yield from 50 kgN/ha less as compared to wheat (see graph below).



*Yield response to N fertiliser for the highest yielding variety of the species of triticale, oats, barley and wheat grown in the same experiment. Triangles show N optima at 5:1 breakeven ratio with standard errors (*Ref: D R Kindred, R M Weightman, S Roques and R Sylvester-Bradley).

Effect of N on yield of triticale and wheat (data points and fitted curves), including yields at optimum N rates (triangles) at a) Towthorpe, and b)Terrington in 2010.



Other datasets in 2007 (ADAS) and 2010 (*Agrovista*) have also concluded the improved yields achieved from triticale above those of wheat. This has been apparent in both 1st and 2nd wheat rotational positions. *Weightman et al* concluded in their HGCA Report 478 that 'Given the higher yield with the same and/or less N, these results clearly indicate that triticale can have higher nitrogen use efficiency than wheat.' The lower nitrogen optima required for the alternative cereals, oats, triticale and rye is recognised in the Fertiliser Manual (RB209) as shown in the tables below:

Oats, Rye and Triticale, winter sown – Nitrogen

	SNS Index						
	0	1	2	3	4	5	6
	kg N/ha						
Light sand soils	110	70	20-50	0-20	0	0	0
All other mineral soils	150	120	90	60	30	0-20	0
Organic soils				60	30	0-20	0
Peaty soils						0-20	

Wheat, Autumn and Early Winter sown – Nitrogen

	SNS Index						
	0	1	2	3	4	5	6
	kg N/ha						
Light sand soils	160	130	100	70	40	0-40	0-40
Shallow soils	280	240	210	180	140	80	0-40
Medium soils	250	220	190	160	120	60	0-40
Deep Clay soils	250	220	190	160	120	60	0-40
Deep Silty soils	220	190	160	130	100	40	0-40
Organic soils				120	80	40-80	0-40
Peat						0-60	

Whilst these alternative options represent an opportunity to reduce nitrogen usage, they do have some limitations due to the poorer qualities of the grain which should be assessed before embarking on their introduction into the cropping program.

The use of crops such as rye, oats or triticale and the development of Synthetic Wheats are largely concepts using the natural genetic diversity and breeding methods found in this crop group. However, there are studies now ongoing that are looking to use other genetic manipulation methods, which is true genetic modification. These breeding programs are very focused on the area of Nitrogen Use Efficiency, with the goals stretching from total nitrogen fixation by plants to the more modest 10-20% reduction in a crop's nitrogen requirement. Within my Nuffield study I embarked on visiting three establishments that were at the forefront of this Genetic Modification research, namely University of Alberta, John Innes Centre and Arcadia. Each of these organisations has slightly different concepts on how to reduce our reliance on nitrogen.

Nuffield Study Visit – Arcadia Biosciences

Arcadia's Mission is :

'To develop plants that improve the environment and human health.'

They were founded in 2003 and are privately owned by the following organisations MCC, Inc.Vilmorin & Cie, CMEA Capital, BASF Venture Capital America, Inc., and Saints Capital. Their headquarters and main R&D facilities are in Davis, California, with additional facilities in Seattle, Washington, and Phoenix, Arizona, with a total staff of 80 of which 60 are directly involved in R & D. Product development has a timeline going from the high risk, low net value, pre proof of concept through to the low risk, high net value, commercialisation. Arcadia currently fits in the middle, optimising from the proof of concept phase through to licensing the technology to commercial partners. In their optimisation process they would use two methods of genetic management:

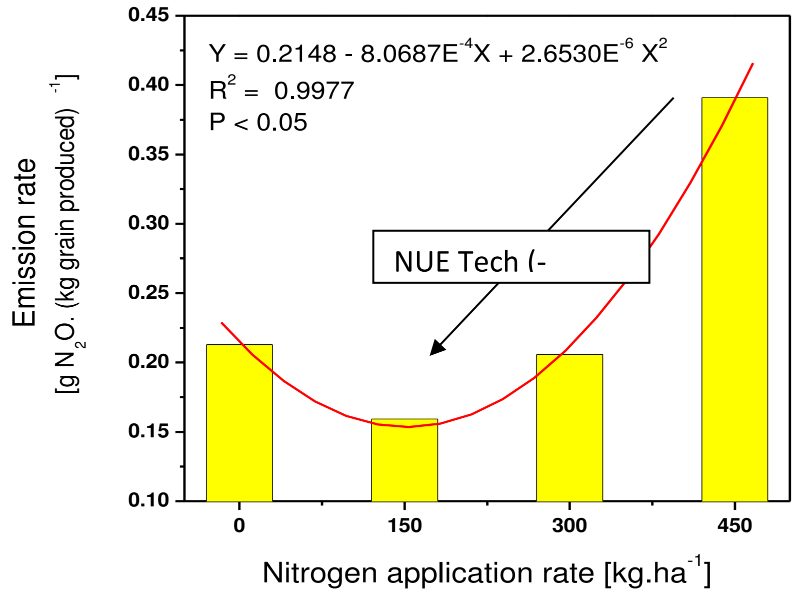
1. TILLING (Targeting Induced Local Lesions IN Genomes) is a general reverse genetic technique that uses traditional chemical mutagenesis methods to create libraries of individuals that are later subjected to high-throughput screens for the discovery of mutations. The process of creating mutants is a relatively imprecise mechanism, but has proved to be effective.

2. TRANSGENIC Relates to an organism whose genome has been altered by the transfer of a gene or genes from another species or breed. Transgenic organisms are used in research to help determine the function of the inserted gene, while in industry they are used to produce a desired substance. The use of the transgenic method is a much more target and precise approach to transferring desired traits from one species to another.

Arcadia aim to have introduced the desired trait into one monocotyledonous crop and one dicotolydenous crop, as well as having some field data to support the agronomic benefit *before* looking for a commercial partner to deliver the variety to the market. Getting the genetically modified crop to the market still represents a long process with a great deal of regulation to comply with. Arcadia have a great deal of experience in this area and have achieved the fastest clearance of a product in their field. This was the GLA Safflower that took 5.5 years (for more detail go to http://www.arcadiabio.com/safflower).

Arcadia has identified the value of specific markets that could benefit from this technology with the one at the top of the list being nitrogen efficiency. They have valued this to be worth $60 billion, which is double the next most valuable trait, namely water efficiency that they put at $25 billion. The value attached to nitrogen efficiency includes both that of its fertiliser value as well as environmental costs associated with it. The latter would be examples of eutrophication costs and Green House Gas emissions. Using crops with high NUE would represent an abatement strategy for farmers across the world, generating carbon credits that could ultimately be traded to offset other emission hot spots. Arcadia is working in Ningxia, China (see pictures below) to develop emissions models for Carbon Credits.

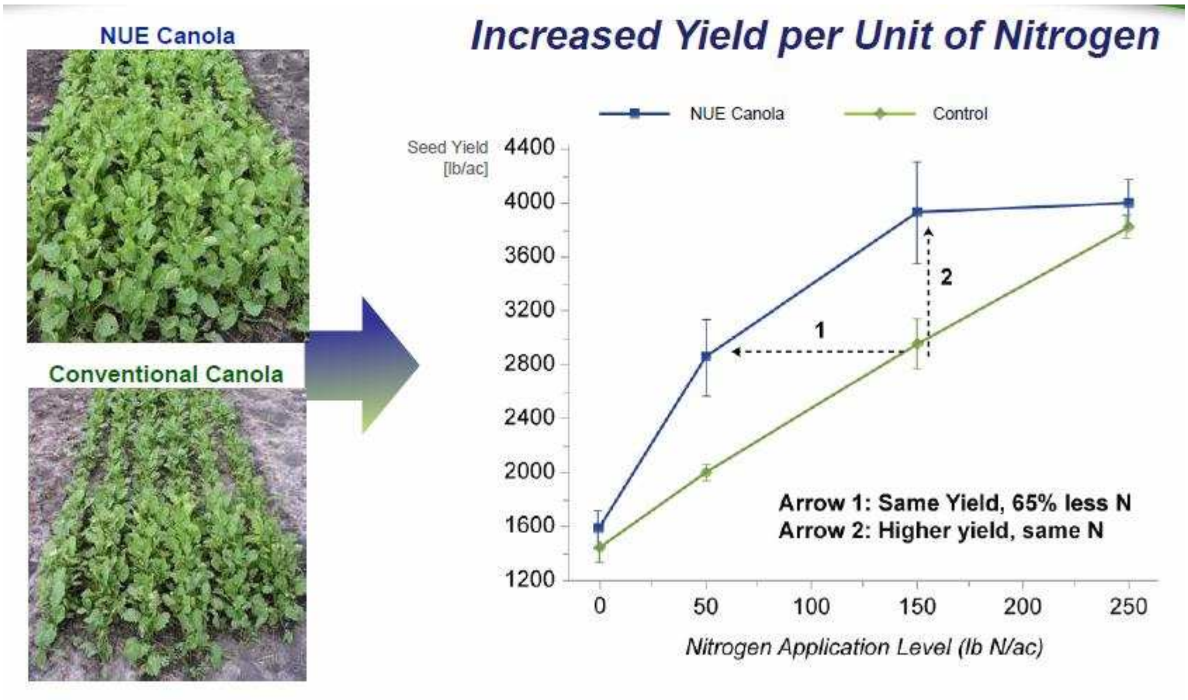
Rice GHG Emissions Data from Ningxia, China



Arcadia has valued the global carbon trading market at approximately $90 billion and they see crop agriculture as one of the most cost-effective sources of carbon credits. Two of their existing small scale precedents demonstrate that IPCC will accept properly qualified crop methodologies so they are continuing to gather baseline data in a five year field trial study with rice in China, and a two year field trial study with rice, wheat, and corn in India (funded by USAID).

To date Arcadia have had success in introducing genes that improve NUE in two crops – canola (oilseed rape) and rice. Taking the canola crop that could be of great value to the UK farmer, they have varieties that are giving higher yields per unit of nitrogen applied. The data below demonstrates this with the highest yields being achieved off 65% less nitrogen applied. If it is assumed this translated into UK agriculture then the current optimum Nitrogen rate in winter oilseed rape would reduce from 225 kgN/ha down to 146kgN/ha. This gives a cost in nitrogen reduction of approximately £65/ha which equates to >£45 million worth of nitrogen over the 700,000 hectare UK crop.

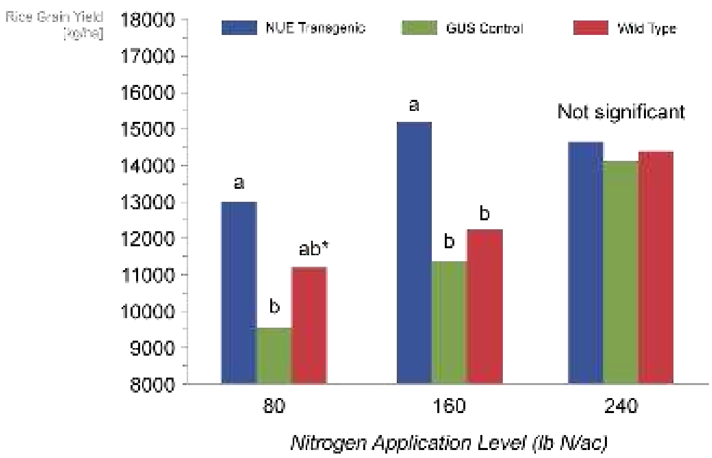
Alternatively this can be viewed environmentally which equates to reducing the loading of nitrogen into UK agricultural by 160,000 tonnes of 34.5% ammonium nitrate. This represents approximately 8% of the annual UK nitrogen fertiliser market.



This improvement in NUE is not through any form of nitrogen fixation, but through improvements in nitrogen recovery via a larger root biomass and better nitrogen utilisation following uptake.

The monocotylednous crop that they have again had success with has been rice. Once again the same traits have been introduced into rice varieties that give an increase in root biomass, subsequently improving the efficiency of nitrogen uptake. Again the levels of improvement from trials was as with the Canola, where comparable yields could be obtained from 65% of the nitrogen application rate.

NUE Rice **Control**

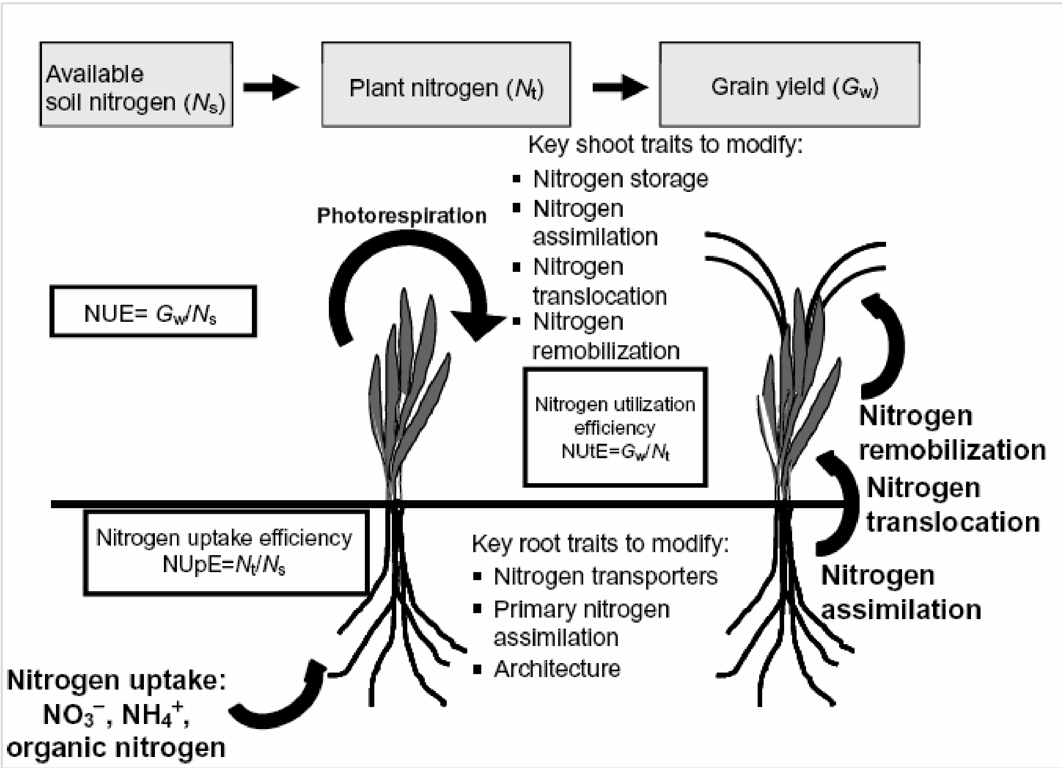


The results being achieved through the use of transgenics demonstrate how this genetic management could have real potential at tackling the 'reactive nitrogen' problem, both reducing the reliance on it, and the impact it has on the wider environment.

My thanks to all the staff at Arcadia Biosciences for sharing there findings and vision for the future and the role transgenics could have in future crop management.

Nuffield Study Visit – University of Alberta – the 'Good Lab'

Improved Nitrogen Use Efficiency has been a subject of interest for some years in the Department of Biological Sciences at the University of Alberta, Canada. A team in the department, led by Dr Allen Good, is interested in understanding how plants adapt to a variety of different environmental stresses, such as flooding, drought or nutrient deficiency. The latter led me to visit Allen and his team to understand further their vision and research focus. The diagram below seeks to identify some of the areas that could be researched as ways of improving NUE.



The nitrogen cycle from soil to plant product. Nitrogen use efficiency (NUE) is determined by uptake efficiency (NUpE) and utilization efficiency (NUtE), which correspond to the amount of nitrogen taken up by the plant NUpE, N t (total plant nitrogen)/N s (total available soil nitrogen). G w is grain yield or weight. NUtE, G w/N t key components (traits) that have been modified and should be evaluated in more detail are shown.

As the diagram above indicates there are some distinct areas which can be considered in attempting to improve the NUE via genetic manipulation:

- Transport of nitrogen into the plant from the soil and into the root

- The primary assimilation
- Secondary assimilation
- Nitrogen signalling i.e. the feedback mechanisms from shoots to roots
- Nitrogen movement around the plant
- Nitrogen storage and remobilization to the sink organs e.g. grain

It is beyond the scope of this report to cover all the possible methods to improve NUE so I will focus on the areas highlighted by the 'Good Lab' at the University of Alberta. There are two areas of interest for them, namely the role of specific aminotransferases and genes involved in amino acid biosynthesis in nitrogen use efficiency: and signalling in plants and biological nitrogen fixation. The former has seen the most progress and essentially is the fundamental process used by Arcadia Biosciences in their development of improved NUE. The latter, nitrogen fixation by non-leguminous plants, is where attention is now turning and is seen by many researchers as the 'holy grail'.

Alanine Aminotransferase (AlaAT) Gene Expression

This concept involves taking the gene that causes the expression of Alanine aminotransferase (AlaAT) activity from barley and transforming it into the desired crop using the bacteria *Agrobacterium tumefacians* to produce the transgenic crop. *Agrobacterium tumefacians* is a bacteria that is abundant in the environment causing galls when it infects plants. It is particularly useful as it has the ability to transfer genetic material from itself directly into cells. This AlaAT enzyme is known to promote the synthesis of the amino acid alanine from pyruvate, a substance produced during plant respiration. It was initially discovered that the introduction of a specific aminotransferase gene (alanine aminotransferase; AlaAT) into oilseed rape could result in these plants outperforming control plants under conditions of reduced nitrogen application. This has now been extended into cereal crops and again the evidence suggests that improvements to the nitrogen use efficiency of rice, by the directed expression of AlaAT, can be achieved. Currently, the technology is being evaluated in rice, barley and wheat in Canada, Australia and the UK. The current and future research of the 'Good Lab' team will continue to focus on the genetics and molecular biology of nitrogen uptake and metabolism in plants.

Genetically modified Barley growing in a petri dish with improved NUE

Genetically modified Barley in a Growth Chamber with improved NUE.

Biological Nitrogen Fixation (BNF)

In Section A of this report I discussed the industrial fixation of nitrogen using the energy intensive Haber-Bosch process to convert inert N_2 into the reactive nitrogen forms ammonium and nitrate. There are two further ways that nitrogen can be made reactive, atmospheric and biological. Atmospheric is through the action of lightning , whilst biological is found only in certain bacteria:

- Some live in a symbiotic relationship with plants of the legume family (e.g. clover, pulses, soybeans, alfalfa).
- Some establish symbiotic relationships with plants other than legumes (e.g. alders).
- Some nitrogen-fixing bacteria live free in the soil.
- Nitrogen-fixing cyanobacteria are essential to maintaining the fertility of semi-aquatic environments like rice paddies.

Biological fixation requires a complex array of enzymes and a large quantity of energy in the form of ATP. The first product of fixation is ammonia which is then quickly incorporated into protein. It has been estimated by scientists that this process adds annually approximately 140 million metric tonnes of nitrogen into the ecosystem. Nitrogen fixing organisms can be grouped as follows:

1. Free living aerobic bacteria
    - Azotobacter
    - Beijerinckia
    - Klebsiella
    - Cyanobacteria (moss, lichens)

2. Free living anaerobic bacteria
    - Clostridium

- Desulfovibrio
- Purple sulphur bacteria
- Purple non-sulphur bacteria
- Green sulphur bacteria

3. Free living associative bacteria
   - Azospirillum

4. Symbiots
   - Rhizobium (legumes)
   - Frankia (alder trees)

Of these groups the Rhizobium (Legume) system and the cyanobacteria (lichens,moss) systems dominate. All the nitrogen fixing bacteria use the same enzyme complex called Nitrogenase which is composed of two subunits: an iron-sulphur protein and a molybdenum-iron-sulphur protein. The aerobic group face special challenges to nitrogen fixation because nitrogenase is inactivated when oxygen reacts with the iron component of these proteins.

There are currently two distinct concepts being considered in the 'race' to achieve biological fixation in non-legume crop plants. One concept is to utilise bacteria from group 1, whilst the other is to utilise the Rhizobium from group 4. The 'Good Lab' is focusing its efforts on the first concept with the aim of using transgenic mechanisms such as that using the Agrobacterium to transfer the genetic code required to achieve nitrogen fixation into a specific organelle in the cells of the crop plants to be transformed. The choice of organelle is critical in that it needs to be oxygen free if possible to prevent inactivation of the nitrogenase enzyme complex. The current thinking is that the chloroplasts or mitochondria could be one such organelle. This would create a cell with the ability to manufacture its own ammonia that can then be used in protein synthesis. Research currently is looking to identify the key gene sequences that cause expression of the nitrogen fixing genes. These genes are often referred to as the 'nif' genes and there are thought to be at least twenty that control the nitrogenise complex. The benefit of this approach is that once achieved the genetic trait should remain in with the crop and be consistent as all the genetic coding will be in the seed.

Nuffield Study Visit – The John Innes Centre

"Welcome to the John Innes Centre, an independent, international centre of excellence in plant science and microbiology. Our mission is to generate knowledge of plants and microbes through innovative research, to train scientists for the future, to apply our knowledge to benefit agriculture, the environment, human health and well-being, and engage with policy makers and the public."

The John Innes Centre (JIC) is a world class research facility and is leading the way in our understanding of crop genetics. The centre was formed from four leading institutes, one of which was The Nitrogen Fixation Laboratory, 1963–1995. It has a long history associated with the Biological Fixation of Nitrogen and has at its core an ambition to produce nitrogen fixing cereals. Research in this area continues under the leadership of Professor Giles Oldroyd.

Professor Giles Oldroyd

The research at JIC differs from that being done at the University of Alberta in the 'Good Lab' as rather than enabling the plant to fix its own nitrogen, they are looking at recreating the symbiotic relationship that exists between legumes and rhizobium. In this relationship the rhizobium bacteria use energy from the plant and in return supply reactive nitrogen in the form of nitrates. The plant can then metabolise this nitrate in to amino acids and protein. The first target of this research is to enable the maize plant to recognise the presence of the soil borne rhizobium from which it can form a symbiotic relationship. It is hoped that if this relationship can be persuaded to happen then nitrogen feeding of the crop by the bacteria will follow. This research has been given recent endorsement with financial support ($9.8m) from the Bill & Melinda Gates Foundation.

Improving the Nitrogen Recommendations

One fundamental area of focus to help farming reduce its reliance on fertiliser is to improve the annual crop and site specific recommendation. Over the years of nitrogen fertiliser use UK farming has generally adopted a risk management attitude towards the rate of application used. With yield increases of typically 150-180%, a level of insurance has been built into the recommendation to avoid 'falling down' the steep part of the response curve. This approach has not been misplaced as it has also compensated for the lack of accuracy that exists within the current UK Fertiliser Manual Recommendations. The recent HGCA guide has also highlighted this with the implication that the winter wheat recommendations are accurate to +/- 50kgN/ha around the optima. In order to improve this accuracy consideration needs to be given to those aspects of the recommendation that contribute most towards the errors. In the most simplistic of calculations the nitrogen recommendation is the difference between the crop's nitrogen requirement and the total nitrogen supply. The crop's nitrogen requirement is a very easily calculated figure using the total biomass and expected nitrogen content. The difficulty then arises when determining the supply side of the equation. This requires detailed understanding of three key elements.

Firstly a measure of the crop available nitrogen in the soil profile is needed. This is now a routine measurement for many leading farming enterprises, with contractors well set up to deliver this analytical process. Soil is cored to a depth of either 60 or 90 cm and sent to a lab for total nitrate and ammonium analysis.

Secondly an understanding of how much nitrogen will be mineralised and thus become available as the season progresses. This measurement does occasionally appear either as a very crude estimate related to soil type or as a more accurate estimate based on a soil incubation process to simulate potentially available nitrogen.

The third essential ingredient in estimating soil supply is estimating an efficiency for the nitrogen recovery which clearly will be associated with root biomass and distribution within the soil profile. Out of these three factors, only the first one has any level of certainty attached to it, so we can predict with great certainty that any estimate of the soil supply required to meet the crop demand will be inaccurate.

In my research for this Nuffield report I hoped that I would come across some innovation in this area that could advance the UK nitrogen recommendations. Unfortunately I did not, however my visit to a Canadian farmer did again make me rethink the possible role that having a better soil mineralisation value to apply to the soil supply calculation could play.

Nuffield Study Visit – Beck Farms, Innisfail, Canada

Rod Bradshaw with Agrologist Ross McKenzie
Beck Farms Innisfail Alberta, Canada

www.innisfailgrowers.com

Whilst visiting Canada I travelled to Innisfail to meet up with Rod Bradshaw and his Agrologist Ross McKenzie to discuss their view on 'Life After Nitrogen Fertiliser'. Rod moved back to manage the 1200 acre, Beck Farms in 1971 following a University education and 2 years with Monsanto. The farm grows various crops including grains, oilseeds, hay, alfalfa, pulses and carrots in rotation. They are fully min till and now operate RTK seeding.

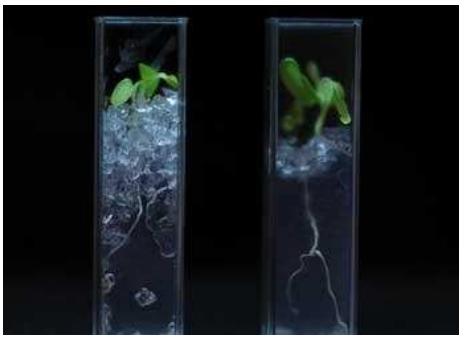
The first response to my question was "*it would be tough!*" followed by "*unless people are prepared to pay double for their produce*". Rod had no reason to consider this as an option, especially as he had no indication that the oil wells that had continued to pump for 50 years on his farm showed any sign of stopping anytime soon. Both Rod and Ross did however see the need to use their fertiliser as efficiently as possible and explained how the farm had moved away from the anhydrous ammonia 10 years ago to a liquid urea based system now. Over the last few years they have also experimented with some novel inhibitors – Agrotain and ESN – neither of which have been convincing in their performance. In terms of Ross McKenzie's fertiliser recommendations he uses all available farm data to develop field specific recommendations. Allowances for yield prediction, available nitrate down to 30cm, organic matter content and seasonal mineralisation are made before a final application rate is set.

The latter is an area of interest for the UK recommendations which do not allow for this. Ross uses a figure of 5lb N/acre/% Organic Matter as an assessment of soil nitrogen mineralisation. Through their own farm experience they feel that this method is accurate for their soil and rotation. To further improve their nitrogen use efficiency and reduce their reliance on fertiliser Rod and Ross are exploring the potential value to them of soil zoning and NDVI (crop scanning) measurements, recycled waste and biodigestate. Ultimately they both concluded that the real solution to reducing nitrogen fertiliser use lay in the hands of the plant breeders who would produce a genetic solution.

My thanks to Rod and Ross for their time during my visit to Canada.

Whilst I did not uncover any new evidence to suggest that our understanding of the dynamics of soil mineral nitrogen are about to be improved, I did come across some shoots of optimism in two areas which could go some way towards filling some of the knowledge gaps:

'The See Through Soil'



Firstly at The James Hutton Institute, Dundee where they have developed The Transparent Soil for imaging the Rhizosphere. The synthetic media that resembles soil is a synthetic composite known as Nafion. The product is a substrate which is very similar to real soil in terms of physical and biological variables, such as water retention, ability to hold nutrients and capability for sustaining plant growth. According to Dr Dupuy, the principal researcher developing this process *"There are many different scientific disciplines that could benefit from this research. Transparent soils could be used to study the spread and transmission of soil borne pathogens. In crop genetics, transparent soils could be used to screen the root systems of a range of genotypes. This would help breed crops with more efficient root systems so that agriculture can rely less on fertilisers. Physiologists could also* *use transparent soils to understand how plants or microbes access nutrients that are heterogeneously distributed in soil."*

DNA Finger printing of soils

The second area of innovation that I discovered is also in its infancy but again could provide the breakthrough needed to help unravel some of the unknowns related to nutrient availability in soils. It has been understood for years that the biological diversity of soils is vast, and plays a critical role in nutrient cycling; however identifying what all the microbes are has been an impossible task. At best probably 10% of the organisms could be identified when cultured on a Petri dish. With science now able to sequence whole genomes the ability to reveal 100% of the biology of the soil has become a reality. The concept of DNA fingerprinting a soil is making the headlines: ***Rapid advances in DNA sequencing paves the way for cutting edge soil sampling*** was one example.

Chris Packham collects a sample from his garden soil. Credit: BBSRC

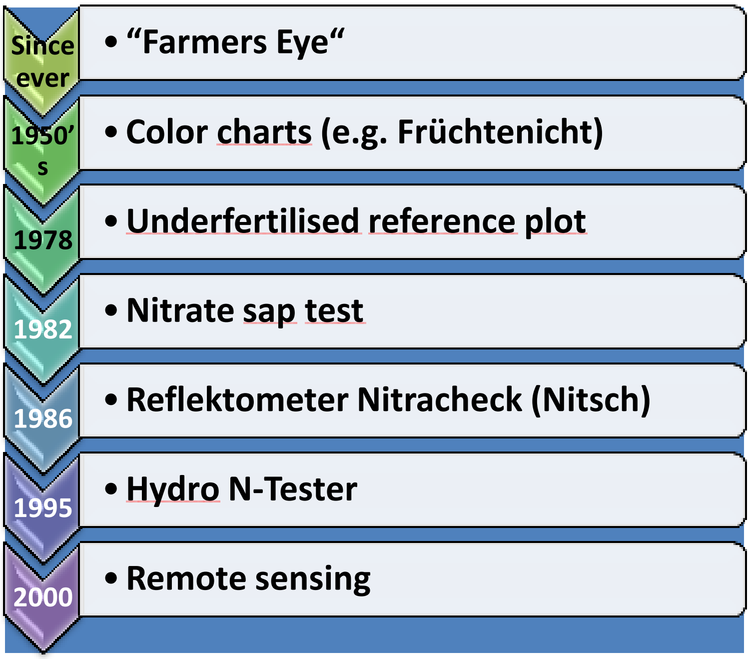
DNA fingerprinting of soils can now be done at The Genome Analysis Centre (TGAC) in Norwich where the sequencing process provides the genetic data in under a week. With technology advancing so quickly in the area of genome sequencing it is expected that over the coming months the week turnaround time will be reduced further. It is expected that future techniques will allow a genome the size of the human to be sequenced in 24hours – 'Genome in a Day'! Such advancements will enable large banks of genetic data to be collated and correlated with specific soil properties. These relationships can then be used in future management of soils to optimise nutrient availability and sustainability.

Improved Nitrogen Management via the Canopy

The rather negative attitudes I encountered around the future of soil nitrogen measurements towards a more accurate recommendation were further supported in Mexico at CIMMYT where Ivan Ortiz-Monasterio, CIMMYT NUE lead researcher quoted "*We have given up with soil nitrogen measurements, using the canopy is the most accurate approach".*

Indeed for some time now commercially available analytical tools have been used in research and on farm to improve the NUE. The first examples of methods used consisted of colour charts in the 1950s through to the first real time sensors appearing in 2000.

Ortiz Monasterio, CIMMYT



Three examples of remote sensing tools available are highlighted below:

The Yara ALS N Sensor

soylsense
variable rate nitrogen

On my visit to CIMMYT in Mexico it was very apparent that they saw the future of nutrient management being directed towards real time crop canopy sensing as a means to improving their recommendations, especially in the wheat crop. There most recent acquisition being the air balloon with on board camera to gather spectral reflectance data from the many experimental plots. Other projects are also evaluating the Minolta Spad meter as a means to improve nitrogen management towards improved grain quality.

Air balloon fitted with a multi spectral camera for crop scanning

Minolta SPAD Meter / Yara N Tester for leaf nitrogen status measurement

As seen in the timeline above, many of these tools have been around for some time, but the uptake has been slow due to the relative cost and lack of independent, statistical evidence to support their use. The ability to evaluate these tools will always be problematic as most of them rely on a calibration process that relies on an initial nitrogen recommendation that is already error prone. As Sensors move towards Absolute protocols whereby the sensor determines the rate, the more the likelihood is that empirical data will prove their value. There is evidence that this technology is becoming more accepted as the number of users increase every year, however, progress is relatively slow. These systems are another bit of the jigsaw to improved NUE and there is a growing bank of evidence that farmers can expect a 3-4 % yield increase having used 10% less nitrogen which represents a definite improvement in NUE.

Conclusions

The original working title of this report was 'Life after manufactured fertiliser' which evolved over time to become 'Fertilisers of the Future'. Having deliberated over the period of the study with farmers, academics and agronomists the striking bit has been the variation in responses. However, there is one common thread that runs through them all and that is without reactive nitrogen life would be tough. This nutrient is such a difficult beast in that in one state it is totally harmless but also useless, while in its reactive state it becomes both extraordinarily important and catastrophically damaging when let loose!

The fears of not being able to manufacture nitrogen fertiliser in the short term have been found wanting with fossil fuel supplies taking us well into the second half of this century and probably into the next. If in the world sustainability does start to drive all decisions rather than the short term economics that do the driving presently, change may have to happen but, as described in section A, renewable energy based fertilisers do look feasible. As well as alternative manufacturing techniques there are options for agriculture such as closer attention to rotations and re-introducing green manure crops but, these come attached with a cautionary note in that the efficiency of uptake of the reactive nitrogen contained within these products is poor giving rise to the very same environmental issues that are impacting on today's nitrogen.

The area that is gaining the most momentum, and attracting the most funding, is that of Genetic Modification towards improved NUE or Biological Nitrogen Fixation of non leguminous crops. This of course is seen as the best result for all concerned – environment, farmers, food security – but is it? Whilst there is improved efficiency of conversion in that the crop takes up nitrogen and converts it to protein bypassing the inefficient root uptake mechanism we are still left with residues of crops, sewage, etc that contain nitrogen. Will this new GM crop ignore this residual nitrogen and continue to fulfil its own requirement from the atmosphere giving rise to continued build up of reactive nitrogen in the soil?

On 13 October 1908, Fritz Haber filed his patent on the synthesis of ammonia for which he was awarded the 1918 Nobel Prize for Chemistry. Maybe the Nobel Prize will go to the winner of the race toward Biological Nitrogen Fixation – 100 years later!

'We don't know what we don't know – so the only way to find out is to give it a go!'

Actions for UK Farming:

To become less reliant on manufactured nitrogen fertiliser:

- Create a Soil Fertility Management Plan to include:
    - A review of the rotation.
    - Research access to local recycled material.
    - Consider the value of Biodigestate and its present or future availability.
    - Review the potential for green manure crops to capture potentially 'lost' nutrient.

- Understand and target Nitrogen Use Efficiency (NUE):
    - Choice of nitrogen source
    - Nitrogen application technology – spreader calibration and Variable Rate
    - Consider other crops with improved NUE e.g. Triticale
    - Monitor the crop canopy to aid nitrogen management.
    - Invest in on-farm trials to determine your crops Nitrogen optima.

Acknowledgements

My thanks to all those who have contributed to my Nuffield Arden Study. Before applying I had heard about the challenges that Nuffield brings – time management, knowing where to go and not to go, keeping your family happy, and when to stop and start writing! They have all been challenges I have faced over the last 12 months. Some I have passed, others I have failed but all in all it has been a fantastic experience that will stay with me forever.

My grateful thanks to the following sponsors that have enabled me to research and study this topic which has the potential to be one of the most exciting and yet controversial subjects during this next century.

Frank Arden Trust

The Crown Estates

Yara UK Ltd

My final and most important thanks go to my family who have supported me throughout.

Mark Tucker

Head of Agronomy
Yara UK Ltd
Harvest House
Europarc
Grimsby
Lincolnshire DN37 9TZ
Mobile : 07766 504778
Email : mark.tucker@yara.com
www.yara.co.uk

References

Erisman, J.W., Sutton, M.A., Klimont, J., Galloway, Z., Winiwarter, W., 2008. How a century of ammonia synthesis has changed the world. Nature Geoscience 1, 636–639.

C.J. Dawson , J. Hilton Food Policy 2011. Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus

Rothamsted Broadbulk data 2012

V.Smil . Energy – Myths and Realities,

V. Smil (2008). Global Catastrophes and Trends: The Next Fifty Years by

Burney, J.A. et al. Proc. Natl Acad. Sci. USA doi:10.1073/pnas.0914216107; 2010

Rockström, Johan et al, A safe operating space for humanity, Nature 476, 282 (August 2011)

Davies, Bill ; Baulcombe, David ; Crute, Ian ; Dunwell, Jim ; Gale, Mike ; Jones, Jonathan ; Pretty, Jules ; Sutherland, William ; Toulmin, Camilla Reaping the Benefits: Science and the sustainable intensification of global agriculture. /.London : Royal Society, 2009. 86 p.

D R Kindred, R M Weightman, S Roques and R Sylvester-Bradley. Yield response to N fertiliser for the highest yielding variety of the species of triticale, oats, barley and wheat grown in the same experiment