Café Scientifique Talk (8/1/18)

Henry Greathead

Use it or lose it!

Slide 1 Title

Good evening ladies and gentlemen. The efficiency with which animals are able to extract nutrients from their diet is the 'food' for thought this evening. The driver behind this topic is the environmental impact livestock farming, animal manure specifically, has on the environment.

I am going to talk about some of what science is doing to try and mitigate against the environmental impact of livestock farming, by way of making animals more efficient at capturing the nutrients from their diets (decreasing nutrient outputs). This topic generally necessitates a close working relationship with animal excrement, for what is not captured by the animal is generally voided in the excrement, faeces and urine.

My professional interest in the subject relates to understanding the efficiency with which ruminant animals, in particular cattle, are able to convert high fibre feeds of low nutritional value into highly nutritious foods (milk and meat), thanks to their complex digestive system. I don't work with cattle manure, I work with rumen fluid!

Slide 2 Outline

I am going to begin by looking back to the time when animal manure was highly valued as a fertiliser and some of the developments that can be attributed to it. Today animal manure is still a valued fertiliser, however, the animal revolution and associated concentration of animal production units now makes it a serious problem, and I will try to illustrate the magnitude of this problem.

As for the science, I am then going to focus on nitrogen (N) and phosphorus (P), two important nutrients in the diet and also serious pollutants in animal manure. I will explain why manures from different animals, cattle and pigs specifically, vary in their N and P content and I will briefly present some of the methodologies being used and researched to improve the uptake of these nutrients by animals, which has the obvious advantage of reducing their output in manure.

Slide 3 Message

For the benefit of those that reach the end of the talk before I do, I will deliver the take home message now. And I must confess I have had some difficulty in deciding on the message: I would like to have concluded science, examples of which I will include in my talk, has the solution to mitigate against the environmental impact of livestock farming on the environment. However, the advances made by science are outstripped by the growing demand for animal protein, particularly in less developed countries (not that they eat a lot, yet, but by virtue of their population size), a demand met by producing more livestock! Therefore, the message is simple, and one I am pleased to say I hear more and more, and that is in order to reduce the environmental impact of livestock farming on the environment we need to reduce livestock numbers and that requires us to reduce our intake of animal protein (and our waste of it)!

Slide 4 Yesterday

No one knows exactly when man discovered animal manure applied to the soil improved plant growth. Certainly for two thousand years all types of organic matter (clay, limestone, chalk, soot, waste from soap and sugar manufacture, tanner's bark, wool, hair, oilseed waste, household waste, seashells, seaweed and of course animal manure), depending upon availability, were applied to soil. The early fertiliser manufacturers were bone crushers. The 1830s saw the most dramatic advances in the understanding of fertilisers. The German scientist Escher in 1835 is thought to have made the discovery that insoluble phosphate (neutral Ca_3(PO4)2, tricalcium phosphate (hydroxapatite)) in ground bones can be made more available to plants by treating the bones with sulphuric acid – superphosphate (acid calcium phosphate Ca(H2PO4)2, which is soluble) was produced.

$Ca_3(PO_4)_2 + 2\ H_2SO_4 \rightarrow Ca(H_2PO_4)_2 + CaSO_4$

$Ca_3(PO_4)_2$ = tricalcium phosphate; hydroxyapatite

$Ca(H_2PO_4)_2$ = monocalcium phosphate; superphosphate

$CaSO_4$ = calcium sulphate; gypsum

But up until the early 19^{th} century no-one understood what it was that made plants grow. Scientists at the time believed all plant fertility came from humus (degraded organic matter in soil).

It is Prof. Justis von Liebig that is credited with being the first person to explain the role of minerals in plant nutrition in a paper delivered to the British Association entitled ‘Chemistry in its Application to Agriculture and Physiology’ in 1837. Unfortunately he believed that plants were able to obtain all the nitrogen they needed from the air and that it was unnecessary to apply it to the soil.

Slide 5 John Lawes and Henry Gilbert

This was firmly disproved by John Lawes (owner of the Rothamsted Manor estate) and Henry Gilbert (scientist; gained his PhD with Prof. Liebig at the University of Giessen in Germany; employed by Henry Lawes to manage the trials he had set up (didn’t have time to run them himself as was too busy running his superphosphate factory in Deptford, which he had set-up after taking out a patent on superphosphate production); a 57-year partnership that is considered to have been the most scientifically productive in the history of food production) with their famous Rothamsted (Hertfordshire) experiments, which began in 1843, initially on turnips. The treatments used in these experiments were mainly with mineral fertilisers (superphosphates manufactured from bones and mineral phosphates (from coprolites – naturally occurring nodules of calcium phosphate in the soil that can be dissolved in sulphuric acid in the same way as bones) by treatment with sulphuric acid), but a few included small amounts of N, and those crops that received extra N gave much bigger yields, showing conclusively that plants needed N in fertilisers or manures for healthy growth. These experiments extended to winter wheat, beans, spring barley, crops in rotation and permanent grassland. These experiments are arguably the longest running and the most famous fertiliser experiments in the world and are known as the ‘Classical Experiments’ – they are still running in the same fields to this day as practical demonstrations.

Slide 6 Guano

Coincidently, 1843 also saw the first shipments of guano (excrement from seabirds and bats) reaching Britain from Peru (guano was mined under appalling conditions by Chinese workers with few surviving longer than 3-4 years from the effects of dust and ammonia fumes). Guano quickly became popular, for with its high N content it produced dramatic results when applied to crops. Guano results in better crop productivity than other farm animal manures, because it has a higher N content. This is because birds excrete waste N in the form of uric acid, which, unlike urea (and ammonia) can be excreted as a dry solid and is therefore a more concentrated form of N.

Two factors distinguished Peruvian guano from other sources of guano around the world:

1. First, the unique weather conditions found along Peru's coast. The Humboldt (Peruvian) Current, which flows cold water from Antarctica to the equator along Peru's coast, creates an interesting weather pattern where the cold water and warm air prevents the fall of rain in this part of the world. Due to the lack of rain on the islands along Peru's coast, the accumulated bird droppings are baked in the dry atmosphere. This preserves the nitrates in the droppings by preventing them from evaporating (ammonification (decomposition of organic N to ammonia) / dentrification (denitrifying bacteria under anaerobic conditions use nitrate instead of oxygen releasing N_2)).
2. The second factor was the enormous fish reserves, consisting primarily of anchovies, found in the seas off Peru's coast. They draw in huge migrations of sea birds, especially the white-breast cormorant, the grey pelican, and Peruvian booby. Because of the islands relative isolation from natural predators, the guano producing birds settle on these islands and raised their young here. Over the course of hundreds to thousands of years and favourable weather conditions, already explained, these birds had accumulated guano reserves up to 60 meters deep. It is estimated that around a million birds residing on an island are able to create over 11,000 tons of guano a year. As the guano originates from fish-eating birds it has a higher N content than other bird guano.

The guano years lasted for only half a century, imports of which peaked in 1870 at 280,000 tons.

Slide 7 Guano....

The sole importer of guano into Britain between 1842 and 1861 was the trading company Antony Gibbs & Sons, which made it a fortune earning it the Victorian music hall ditty:

The House of Gibbs that made their dibs
By selling the turds of foreign birds

By the turn of the 20th century Antony Gibbs & Sons was focused on banking and insurance and became one of the City of London's most successful merchant banks. Its fertiliser business became part of Fisons (a company founded by Joseph Fison in 1843, the son of a flour miller and baker (millstones were used to grind coprolites), on manufacturing superphosphates), a multinational pharmaceutical, scientific instruments and horticultural chemicals company headquartered in Ipswich; acquired by Rhone-Poulenc in 1995.

Antony Gibbs & Sons was floated on the London Stock Exchange in 1973, was bought by HSBC (Hong Kong & Shanghai Banking Corporation) in 1981 and is now part of global insurance company Marsh & McLennan.

In addition to founding one of the City of London's most successful merchant banks and contributing to the success of others, e.g. Fisons, animal manure in the form of guano also had a role to play in the development of London's sewage system for prior to the introduction of guano from Peru much of London's sewage was carted away to the fields on the edge of the city where it was spread on the land for growing vegetable and fruit crops, which negated the need for a sewage system. However, the arrival of guano in the 1840s dramatically reduced demand for sewage and the Victorians were obliged to devise new systems for handling London's waste products, i.e. a sewage system.

Also attributed to guano (manure) is the Plimsoll Line on cargo ships. Samuel Plimsoll was both a partner of Anthony Gibbs and also a member of parliament. He became so concerned over the losses of life and cargo from overloaded ships that he lobbied for improved safety laws. This resulted in the introduction of the Merchant Shipping Act in 1876, which required all ships to be painted with the Plimsoll Line (a line on a ship's hull indicating the maximum safe draft, and therefore the minimum freeboard for the vessel in various operating conditions).

> ***A pub story (truth questionable!):***
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> ***Here's a little history about manure.*** *In the 19th century, everything had to be transported by ship. This was also before commercial fertiliser's invention; so, large shipments of manure were common. It was shipped dry, because in dry form it weighed a lot less than when wet, but once water (at sea) hit it, it not only became heavier, but the process of fermentation began, of which a by-product is methane gas. As the stuff was stored below decks in bundles you can see what could (and sometimes did) happen. Methane began to build up below decks and the first time someone came below at night with a lantern, BOOOOM! Several ships were destroyed in this manner before it was determined just what was happening. After that, the bundles of manure were always stamped with the term "Ship High in Transit" on them, which meant for the sailors to stow it high enough off the lower decks so that any water that came into the hold would not touch this volatile cargo and start the production of methane. Thus evolved the term "S.H.I.T." (Ship High in Transit) which has come down through the centuries and is in use to this very day. It is not a swear word after all, and, you probably did not know the true history of this word.*

Slide 8 Today

Today animal manure is still a valued fertiliser; something garden enthusiast know all about – a 2.25 kg box of chicken manure pellets from Wickes will set you back £5.99, as well as those that live in the country – come the 31st January farmers will be spreading manure and slurry (farmers are not allowed to spread manure and slurry from the 1st October until the 31st January).

Manure is an excellent fertiliser for crop production and if applied at rates equivalent to plant needs then environmental impacts are minimal. However, the animal revolution driven by the food revolution and the concentrated nature of animal production units means animal waste has become a serious environmental problem.

Slide 9 Food and livestock revolutions

Food revolution: driven by population and income growth

The food revolution describes the human appetite for animal protein/products, which is largely being driven by income growth. Using meat as an example, today the average per capita meat consumption is 41 kg/year. Please bear in mind the range: Bangladeshi's eat *ca* 4 kg/year, while Americans eat *ca* 120 kg/year. By 2030 it is estimated global per capita meat consumption will increase to 45.3 kg/year. When multiplied by the world population (today = 7.6 billion; 2030 =8.5 billion) this means an extra 75 million tonnes more meat will need to be produced (*ca* 25% increase on 2015 production).

World meat consumption (kg/capita)

- 1980 = 30.7
- 2015 = 41.3 (35% increase on 1980)
- 2030 = 45.3 (10% increase on 2015)

By 2030 will be producing an extra:

- 75 million tonnes of meat (25% increase on 2015 production levels)

- 158 million tonnes of milk (22% increase on 2015 production levels)
- 38 million tonnes of eggs (20% increase on 2015 production levels)

(i.e. ca 271 million tonnes more animal products)

Livestock revolution: demand driven revolution

The increase in demand will largely be met by an increase in livestock numbers (also increased animal productivity, e.g. heavier animals); there will be 175% more livestock in 2030 (30 billion livestock) compared to 1980 when there were only 10.9 billion livestock.

Expansion in animal numbers

- Will be 60% more livestock in 2030 compared to 2000 when were 19.186 billion livestock; 2030 estimated will be 30.033 billion livestock (11 billion more animals)
    - 65% more poultry
    - 22% more pigs
    - 21% more sheep
    - 24% more cattle

Slide 10 Manure output

Livestock produce manure; lots of it. Focusing on cattle and pigs let's have a look at how much. Your typical cow produces 40 kg/d, and your typical pig 7 kg/d. Multiply this up by the average UK herd size and a dairy farm produces 5.7 tonnes of manure per day; a pig farm produces 3.2 tonnes/d. Multiply this up further for the global herd and cattle produce on average 59 million tonnes/d; pigs 7 million tonnes/d.

Slide 11 Consider...

Consider how much manure is being produced daily on some of the world's largest dairy and pig farms:

China's biggest dairy farm: 40,000 cows (plans for a dairy with 100,000 cows!)

- Owned by China Modern Dairy, the largest dairy farming company in China and the largest raw milk producer in China. The group owns 22 dairy farms and almost 200,000 cows in total.
- The farm milks 20,000 cows at a time with eight rotary parlours of 80 cows
- Each barn is almost 4 ha

Agrosuper: largest pig producer in Chile. Pig farm near Freirna houses 500,000 pigs.

Slide 12 Soya

In 2012 China imported 60.8 million metric tonnes of soy, mostly from Brazil and the USA, a great deal of which is used in animal feed as a protein supplement. Nutrients are being exported from one part of the world to another; they are being concentrated up in very small areas of land (nutrient loading); there is insufficient land to spread these nutrients on; ideally they would be spread back on the land from where they came, i.e. nutrient cycling.

Farm animals currently consume 35% (650 million t) of all cereals (2.1 billion t), 95% of the commercial soybean harvest (soybeans are the primary plant-based protein supplement fed to animals) and a third of commercial fish catches (130 million tonnes of fish (producing 30 million tonnes of fishmeal (Feed Tech 11.1 2007)) fishmeal is an excellent source of dietary protein).

By 2030 cereal consumption by animals is predicted to rise to 41% (1.15 billion t) of the total harvest (2.8 billion t). This means 500 million tonnes more cereals will have to be produced just to meet the needs of our animals.

Slide 13 Science

So, what is science doing to mitigate the problem? One of the main efforts is the improvement feed conversion efficiency, i.e. improving the capture and utilisation of feed nutrients by animals. This reduces nutrient output in manure, i.e. reduces nutrient loading, reduces the nutrient needs of animals, which reduces the pressure on feed production, and of course this improves farmer income!

Slide 14 Nutrient outputs (N & P)

And a good place to start is by comparing nutrient outputs, and thus nutrient utilistation efficiencies, of different animals. From here on in I am going to focus my attentions on nitrogen and phosphorus utilisation in cattle and pigs. On a weight-for-weight basis cattle more efficient than pigs at capturing dietary phosphorus, and pigs are more efficient than cattle at capturing dietary nitrogen (protein). An understanding of why this is so goes a long way to helping develop strategies to improve nutrient capture, thus reducing the faecal nutrient concentration, which helps mitigate against the environmental impacts of animal manure.

Slide 15 Comparative digestive physiology

The differences in N and P utilisation by cattle and pigs are largely explained by the differences in their digestive physiologies. Cattle are ruminants, meaning they have a four chambered stomach with pre-gastric fermentation. Pigs, like us, are non-ruminants, simple stomached animals; microbial fermentation takes place in the large intestine (caecum and colon), i.e. after the small intestine. , Most digested nutrients in the diet are absorbed from the small intestine.

Slide 16 Protein digestion in cattle

Ruminant animals, e.g. cattle, are less efficient than simple stomached animals, e.g. pigs, in their utilization of true dietary protein. (But they can upgrade non-protein nitrogen (NPN; e.g. urea, ammonia) into useful protein, which simple stomached animals can't). N losses from ruminants are exceptionally high, particularly in grazing animals - <u>only ca 20-30% of ingested N can be traced through to meat or milk</u>. Thus, ruminant farming generates vast quantities of N-rich waste. This is an environmental as well as economic problem.

This problem stems from the fact that fresh forage diets promote the growth of proteolytic bacteria, which combined with the fact that the protein of fresh forages is very degradable (<u>fresh forage proteins are almost totally (ca 85%) degraded in the rumen</u>) means the rate of dissimilation of dietary crude protein is rapid and often exceeds microbial requirements for NH_3 (ammonia is the preferred source of N for most microbial protein synthesis) such that rumen ammonia levels normally increase on such diets, such that there is an excess of ammonia. The excess ammonia is absorbed across the rumen wall, converted to urea in the liver and is subsequently excreted in the urine (some is recycled back to the rumen).

<u>Approximately 60% of non-ammonia nitrogen (NAN; protein and amino acids) flowing to the duodenum is of microbial origin</u>, i.e. most of the animal's amino acids are provided by microbial cells. Bacterial protein is readily digested in the small intestine and constitutes a well-balanced array of essential amino acids.

Because most dietary glucose is fermented in the rumen little is absorbed from the small intestine. Glucose is an essential nutrient for all animals and thus much of a ruminants circulating glucose is produced via gluconeogenesis and one of the substrates used are amino acids. Gluconeogenic amino acids are deaminated and the resulting N is excreted.

Because of this inefficiency high performing ruminant animals are frequently protein deficient when fed forage diets. One of the ways of overcoming this protein deficiency is to supplement the diet with additional protein, e.g. soy protein. This is not a sustainable solution. Firstly protein supplements are one of the most expensive feed ingredients, therefore using them significantly increases feed costs, which is something all farmers strive to minimise – feed costs account for 50-85% of production costs (financially unsustainable). Secondly, and from the point of view of this talk more importantly, this strategy is environmentally unsustainable – it exacerbates the pollution problem.

Slide 17 Solutions

Solutions to the inefficiency with which ruminants capture dietary forage protein can be divided into those that aim to accommodate the problem of the rapid digestion of forage protein, i.e. maximise the capture of ammonia nitrogen by stimulating microbial protein synthesis, and those that aim to limit the degradation of forage protein.

Ensuring availability and synchrony of nutrient supply to the rumen microorganisms is key to maximising capture of rumen ammonia as microbial protein. It is the supply of energy that has arguably the greatest effect, and it is for this reason a modest amount of cereal is often included in ruminant diets. Feeding a readily available source of carbohydrate with a forage diet can reduce rumen ammonia concentrations by 45% and increase microbial protein flows to the small intestine by nearly 30%. Obviously the feeding of cereals in undesirable so grasses (e.g. ryegrass) is being bred for high sugar content.

[Also, agro-industrial by-products, e.g. glycerol; live yeast cells (*Saccharomyces cerevisiae*)]

Methods to limit the rate of proteolysis in the rumen include exploitation of the protein binding properties of condensed tannins (plant polyphenols; 2-7% of DM). Feeding *Lotus corniculatus* to lambs reduced rumen ammonia concentrations by 30%, with concomitant improvements in live-weight gain.

Polyphenol oxidase (PPO), an enzyme found in plants at varying concentrations (responsible for browning of fruit & vegetables when damaged). High concentrations found in red clover (*Trifolium pratense*), cocksfoot (*Dactylis glomerata*). The enzyme catalyses the oxidation of diphenols (found in plant vacuoles) to quinones. The quinones rapidly polymerise with reactants, which, if proteins, will limit their digestibility in the rumen reducing the flow of NPN to the duodenum.

[Also, heat treatment; control plant protein auto proteolysis; select against principle proteolytic bacteria, e.g. *Prevotella ruminicola*, *Clostridia sticklandii*); select against rumen protozoa]

Slide 18 Phytate digestion in pigs

It is digestive inefficiencies/incapability's of pigs that makes their manure rich in phosphorus. Phosphorus is an essential mineral element in the diets of all animals (bone metabolism, energy metabolism, phosphoproteins, nucleic acids and phospholipids). However, the availability of the P from plant seeds to non-ruminant animals is very low. This is because 70-80% of the P is in the form of phytate (inositol hexaphosphate, its salt form), the storage compound for phosphate groups in plants especially seeds. To release the P from phytic acid the enzyme phytase is required.

Mammalian phytase (produced by the mucosa of the small intestine) has very low activity, so much so that it is considered negligible. Microbial phytase on the other and is very active (100+ fold greater than the activity of mammalian phytase). This means non-ruminants are unable to utilise phytate P, which passes out of the animals in the faeces in a concentrated form. The P is then enzymatically released by soil and waterborne microbes. In areas of intensive animal agriculture P from animal waste is a serious environmental pollutant, being the major cause of eutrophication (O_2 depletion due to excessive algal growth) of watercourses. In addition, phytate (ionised; negatively charged) is a chelator (an organic molecule that binds metal ions); it has strong binding affinities for important cation (positively charged) minerals, such as calcium, magnesium, iron, and zinc. When a mineral binds to phytate it becomes insoluble, precipitates and is non-absorbable in the intestines. Phytate is thus an anti-nutritional factor.

Ruminants on the other hand are able to utilise phytate P thanks to the actions of microbial phytase in the rumen – phytate P is released in the rumen which the animal is then able to absorb when it passes through the small intestine. The actions of microbial phytase in the large intestine are ineffectual as the P released is not absorbed from the large intestine.

Deficiency of P results in a number of symptoms: rickets/osteomalacia (softening of bones), poor fertility, reduced milk yields, reduced egg yield, reduced hatchability and shell thickness, subnormal growth and pica (an appetite for non-nutritive foreign materials, e.g. wood and bones).

Slide 19 Phosphate supplementation

Therefore, pig diets are supplemented with inorganic phosphate, mono- and di-calcium phosphate (mono-calcium phosphate = superphosphate). This inorganic P is mined in the form of phosphate rock (also known as phosphorite). Commercial reserves estimated to be 65 Gt (50 Gt (77%) in Morocco/western Sahara). Assuming a 2.5% annual increase (current increase rate = 6%) in extraction rates means there are only *ca* 120 years supply left.

Therefore, to supplement is not sustainable; reserves of inorganic P are limited, and, as was the case for N supplementation, it only exacerbates the pollution problem – it does not improve animal productivity through feed efficiency. To be sustainable solutions must seek to redress the inefficiency of P utilisation.

Slide 20 Solutions

Methods to improve the efficiency of utilisation of P from plant feedstuffs are all based on GM methodologies.

Although the benefits of adding microbial phytase to the diets of non-ruminants has been known since the late 1960s it is only in the last 20 years that its use has been made commercially viable. The limitations were cost and the fact that the enzyme is inactivated by the high temperatures required for pelleting feed (+80°C) (post-pelleting spray apparatus has been developed). Advances in biotechnology, including GM technology, are increasingly overcoming these limitations. Commercially available microbial phytase is harvested from microorganisms, e.g. fungi: Aspergillus (mould) species (spp.), Saccharomyces (yeast) spp., and *E. coli* (bacteria) that over express the phytase gene.

Phytase is also now being produced by transgenic crops: oil seed rape (canola), alfalfa, barley, maize, soybeans and rice plants.

A group of researchers at the University of Guelph in Canada have developed a new breed of pig, trademarked 'Enviropig™', which has been genetically modified to overexpress an *E. coli* phytase gene in their salivary glands (parotid glands). These pigs produce phytase in their salivary glands, which is secreted in their saliva and acts in the stomach to make available phytate P.

These strategies improve animal productivity through improvements in feed utilisation and reduce the faecal P content by 60-70%, thus reducing the impact of pig (and poultry) production systems on the environment.

Slide 21 Message

Reduce our intake of animal protein.

Recommended daily protein intake = 0.75 g/kg/day (BNF)

- 75 kg person = 56 g protein/day
    - Average protein intake in UK = 88 g/d (men), 64 g/d (women; gender average = 76 g/d)
    - Average protein intake in USA = 82.3 g/d (men & women; Pasiakos et al., 2015)
    - In the EU animal protein accounts for 55-73% of protein intake (Camilleri et al., 2013)
    - In the USA animal protein intake accounts for 62% of protein intake (plant protein = 30%; Pasiakos et al., 2015)
    - In Egypt animal protein intake accounts for 15% of protein intake
- **Therefore reduce total protein intake: 76 g/d →56 g/d (decrease by 36%)**
    - **Reduce proportion of animal protein relative to plant protein: 64% → *ca* 30% (i.e. decrease by *ca* 50%)**

Slide 22 Thank you