



# The International Fertiliser Society

## RESOURCE OR WASTE: THE REALITY OF NUTRIENT RECYCLING TO LAND

by

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## **ABSTRACT.**

The recycling of plant nutrients in agriculture through the use of organic manures, biosolids and other organic wastes is discussed with special reference to phosphorus (P) and its efficient use in crop production. The benefits and limitations of different approaches to recycling are developed from a historical overview to the present day to show that waste disposal can be replaced by the effective and efficient use of wastes as part of recycling nutrients. This is especially important for P because of the limited global supply of this element, an essential constituent of all living cells. Public perception and acceptance of some aspects of recycling plant nutrients will need to be addressed with urgency. Legislation on the use of various soil amendments will need to be unified, certainly within the enlarged European Community, and preferably globally. Suggestions are made for developing a more unified approach to legislation governing the agricultural use of materials currently considered wastes, and secondary and co-products from industrial processes so that these materials can be used with advantage to conserve resources.

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**Keywords:** Recycling, plant nutrients, phosphorus, fertilisers, biosolids, manures, nutrient use efficiency, energy use efficiency, legislation on recycling.

## 1. INTRODUCTION.

### *'Waste not, want not'*

This phrase, much used in my early teenage years during the Second World War, has in four short words a very simple but important message. But what is it that we waste and how do we waste it? If there is waste how do we prevent it, or can we recycle it in whole or in part? If waste contains valuable constituents then they should be recycled but can recycling be done readily and perhaps more importantly is it economic to do so. In recent years, there has been an increasing awareness of how limited are some of the world's resources, how best to conserve those in short supply and how to ensure that the use of any resource has minimum adverse impact on the environment.

The Conference, at which this paper was presented, was about agriculture, the nutrients required to grow plants and the possibilities of recycling those nutrients in an effective way. Much of this paper is devoted to phosphorus (P). Phosphorus is essential to all life forms and no other element can replace it in its vital role in many physiological and biochemical processes in all living cells. Consequently, the production of crops for food, feed, fuel and fibre requires an adequate supply of P in the soil. But globally, P is a limited resource and there is concern about the rate of exploitation of this non-renewable resource to meet current demand.

These are major issues globally and they are not going to be solved easily, but a start has to be made somewhere. So it is interesting to look at what has happened in the past and the lessons that might be learnt. As a background to this paper, the global resource of P is very briefly discussed. Then some case studies are presented where the starting material was considered a waste and its use in one form or another has resulted in some recycling of plant nutrients. A recent review of the efficient use of P in agriculture discusses opportunities to lengthen P reserves by using P more efficiently. Some future possibilities and needs are discussed in relation to improving the recycling of nutrients for the benefit of conserving resources.

## 2. BACKGROUND.

Phosphorus is a common element, ranking 11<sup>th</sup> in order of abundance in the earth's crust, but the concentration in most rocks is too small to make recovery of the P financially possible. Globally, rocks that contain sufficient P to make it possible to consider its recovery consist of reserves and resources (or potential reserves). Reserves are deposits that are currently exploitable in an economically viable way. Resources are deposits that could be used subject to advances in processing technology or their use becoming economically viable. Both reserves and resources have a finite life span. In 2006, the US Geological Survey estimated the world phosphate rock (PR) reserves at about 18,000 million tonnes, while the resources were about 50,000 million tonnes (Jasinski, 2006). The International Fertilizer Industry Association (IFA)

estimated world PR production at 171 million tonnes in 2005 (Prud'homme, 2006). At this rate of use, the reserves and resources could last between 105 and 400 years. However, it is difficult to ascertain the true extent of the world's P reserves and resources (IFDC/UNIDO, 1998). Based on some other estimates of potential resources, the global P supply could last between 600 and 1,000 years at the current rate of use (Isherwood, 2003). However, the fact remains that the total global P supply is finite and that it is necessary to use P efficiently to maximise its life span, because life on earth for the anticipated population without available sources of P is inconceivable.

Currently, of the total global production of PR, mineral phosphatic fertilisers account for about 80%, animal feeds about 5%, while 15% goes to industrial uses such as detergents (12%) and metal treatment (3%) (Heffer *et al.*, 2006). When such a large proportion of world PR production is used in agriculture, improving the efficiency with which it is used will increase the life span of world P reserves and resources. Improvements in P use efficiency are discussed in Section 5. A further improvement will be possible if the P used in detergents is recovered from biosolids (sewage sludge) for use in agriculture and this is discussed in Section 3.

### **3. SELECTED CASE STUDIES.**

#### **3.1. Recovering the phosphorus in bones.**

From 1770, making handles from bones for cutlery in the Sheffield area of England produced large amounts of trimmings. This waste was dumped on the land, which continued a long tradition of disposing of many kinds of waste! However, it took time to appreciate that this waste material was having beneficial effects on the yields of dairy pastures in Cheshire and turnip fields in Lincolnshire. By the early 1800s, the manure value of ground bones was well recognised – a unique feature of English agriculture – a waste could be worth money! By 1815, bones were being imported from the Continent and by 1837 imports of 46,000 t were valued at £255,000. The British domestic supply of bones at that time was 27,000 t. However, if bones were to be used effectively, they had to be ground to small particles. Most small ports on the east coast of England, to which continental imports came, had a mill to crush bones. Bones of British origin probably travelled only short distances from source and back to the land on which they were applied. But ground bones did not improve the growth of crops on all soils. This was especially so for turnips and swedes required to feed animals over the winter period in the Harpenden/St Albans area and there was much discussion as to why this might be.

Many attempts were made to solubilise bones. J. B. Lawes, owner of Rothamsted, a small agricultural estate near Harpenden, worked out the correct strength of sulphuric acid and the ratio of acid to bones to produce a dry product. This could be crushed to a powder to apply to land where it was shown to benefit the yields of crops grown on a wide range of different soils.

Lawes took out a patent for his process in 1842 and started manufacturing superphosphate from bones at a factory in London in 1843.

In the 1830s, Lawes brought together a number of factors to solve the problem of lack of effectiveness of crushed bones on his farm. He had a keen and enquiring mind, used a scientific approach, carried out much experimental work in the laboratory and some field experiments, and importantly had sufficient money (although this was Lawes' own money) to carry the work through to a conclusion. The result led to a waste being converted to a very effective, easy to handle product that helped increase the productivity of large areas of P deficient soils. And not only that, a method had been found to recycle P. Of course, Lawes was dealing with only one waste of relatively uniform composition and containing just the one element of interest. In addition, relative to the total amount of P in agricultural produce, the amount in bones was small but, never the less, ingenuity and patience had been successful. The demand for superphosphate quickly outstripped the ability to produce sufficient using only bones and Lawes went on to use coprolites and later phosphate rock. Learning how to successfully get rid of a waste opened up the opportunity for developing the phosphate industry. But the increasing demand for phosphatic fertiliser to increase food production is using up the world's reserves of phosphate and ways must now be found to recover as much as possible of the phosphate that enters the food chain. The scale of the present issue is much greater than that which faced Lawes 180 years ago, but a solution was found then by only a handful of people. Do we not have sufficient ingenuity and skill to solve the present day problem?

### **3.2. Farmyard manures.**

In the context of this paper, farmyard manures is used here as a generic term for all manures derived from animal excreta. Until perhaps 200 years ago, agricultural production was limited by lack of mineral elements – nutrients – required by plants, and which plant roots took up from the soil solution. The two- and three-field system of cropping adopted in most parts of England from the 13<sup>th</sup> century required one of the two or three fields to be rested for one year in rotation to restore its fertility. This restorative year allowed the release of P, potassium (K) and magnesium (Mg) by weathering of soil minerals and the accumulation of a little organic matter when weeds and other plant material was ploughed in. Where a few animals were kept over winter the dung they produced would also be applied to the land. In 1563, Palissy stated that 'you will admit that when you bring dung onto a field it is to return something that has been taken away'. But animal production was limited by lack of sufficient feed for the animals over the winter period. Because dung was the only way of returning 'something to the land', it is not surprising that from the early 1840s, in early experiments testing fertilisers, their effects were compared with those of farmyard manure (FYM).

Without doubt the introduction of the Norfolk 4-course rotation (turnips or swedes, spring barley, a grain or herbage legume crop, and winter wheat) in the mid-18<sup>th</sup> century made it easier to provide feed for animals over the winter

period. Thus it was possible to satisfy an increasing demand for meat and milk by the urban population. More animals required more feed over winter and this meant more FYM. At that time the agreement between most landlords and their tenants farming the land was that only cereal grain and animal products could be sold off the farm. Consequently only small amounts of plant nutrients left the farm and to some extent the fertility of the soil was decreased only slowly. In 1875, Johnston and Cameron (1877) prepared a nutrient budget for the 9.5 million hectares of arable land then cultivated in Great Britain (at that time including all Ireland). There was a large negative balance for nitrogen (N) and K and a small positive balance for P, due to P imported onto farms in animal feedstuffs. Then as now there would have been large losses of N when animals were housed and were grazing in grass fields. Even under carefully controlled conditions to minimise N losses, Voelcker and Hall (1902) estimated that when bullocks were housed and every effort taken to avoid losses, about 15% of the N taken in by the animal as feed was lost. They showed that a further 15% of the N was lost during storage. They considered that a further 20% of the N could be lost before the FYM was incorporated into soil. Thus, where FYM was made, about 50% of the total N fed to animals in their diet could be lost by the time FYM was incorporated into the soil.

By 1939, Cooke (1967) estimated that the major part of the plant nutrients on most farms in England and Wales came from FYM. However, by 1957, FYM was only supplying about 20%, 25% and 65% of the N, P and K, respectively, applied to crops. Church and Leech (1983), using data from the Survey of Fertiliser Practice for England and Wales, estimated that in 1982, only about 15% of tillage crops and 39% of all 'enclosed' grass received manure. However, they did point out that there were large differences between the different geographic regions that were sampled. These proportions of crops and grass receiving manures have changed little subsequently. For the ten-year period ending in 2006/07, the British Survey of Fertiliser Practice shows that less than 20% of all tillage crops and about 45 and 40%, respectively of grass under and over 5-years old received organic manures.

This apparent decrease in the reliance on the nutrients in organic manures in present day farming is probably due to a number of factors. It has occurred despite an increase in total livestock numbers but a decline in mixed farming systems in which both crops and animals were on the same farm. There has also been a large increase in the amounts of inorganic fertiliser used and this can be justified by the increased yield potential of most tillage crops and the judicious use of crop protection chemicals that allow crops to achieve their increasing yield potential.

The trend away from mixed farming systems has resulted in many farms with no access to organic manures, while many others have quantities of plant nutrients in animal excreta far in excess of their cropping requirements. In the latter case these extra nutrients have been brought on to the farm in feedingstuffs and with current concern about P use and recycling some way

has to be found of returning this P to the soil on which crops are grown. The intensification of livestock farming has brought about another change, namely from solid to liquid manure (slurry) systems for ease of handling but with much increased volumes of material involved.

Simplistically it might seem appropriate to take farm-derived organic manures from farms where there is too much manure to others where there is none. However, there are many logistical and energy issues involved when considering such transfers and these are discussed in detail by Fealy (2008, this Conference).

One of the long-standing issues with the use of farm-derived manure and dried poultry manure, which can be readily transported and applied to land, is the 'immediate' and longer term availability to crops of the three major nutrients in manure. Here we can distinguish between N, and P and K. The immediate availability of P and K in manures is important when they are applied to soils below the appropriate critical level (the target Index, see Section 5). If there is sufficient plant-available P and K in the quantity of manure that can be spread on a field then there is no need to apply any fertiliser P and K. Where the manure will supply too little P and/or K then it will be necessary to make good the short-fall with fertiliser. Frequent applications of manure can increase the plant-available P and K in soil quite quickly and the soil should be sampled and analysed every 3-5 years to monitor changes that are taking place. With environmental issues becoming ever more important in relation to land management, one such issue is the transfer of P from land to water. Johnston and Dawson (2005) discussed this issue in some detail and there does appear to be an increased risk of such transfers where large amounts of slurry are applied to soil under unsuitable conditions.

There is often much more doubt about the amount of N that manures will supply in the year of application and subsequently. Not only does N play a major role in yield formation, but too much or too little N can greatly affect the quality of the harvested crop. Various methods are being developed to rapidly measure the N content, especially of slurry, and this is a topic of a later paper to be presented at this Conference.

Presently, average values for the total and available nutrient content of a wide range of farm-derived organic manures frequently available in the UK are given in MAFF (2000). These values are being updated in a revised edition of RB209 that is in preparation and will probably be called the Fertiliser Manual. In general, the proportion of the total P and K that is considered to be immediately available is very similar for both solid manures and slurries.

### ***3.2.1. The availability of phosphorus in farmyard manure.***

Not only is the recovery of P from waste materials important but its immediate and longer-term availability is important too. Average values for the immediate availability of the P in a wide range of organic manures is given in RB209 (MAFF, 2000). Farmyard manure, besides adding nutrients to

the soil, also adds organic matter that increases the amount of soil organic matter (SOM). This increase in SOM can have an additional benefit in that it can provide low energy bonding sites for P so that more of the added P remains readily plant-available (see Section 5). In the long-term experiments at Rothamsted and Woburn soil organic matter has increased where large amounts of FYM (35 t/ha) have been added for many years (Johnston and Poulton, 2005). In the 1950s-1970s soil samples (0-23 cm) were taken from many of the plots in these long-term experiments that had received either fertiliser P or FYM or no P. The soils were analysed for total and Olsen P and also for P soluble in 0.01 M CaCl<sub>2</sub>. The latter solution has about the same ionic strength as the soil solution in neutral and slightly calcareous soils and thus could extract about the same amount of P that would be in the soil solution and immediately available to plants. The FYM- and fertiliser-treated soils contain much more P in all three fractions than do soils without additional applied P.

In each experiment, the increase in total and Olsen P above that in the control was very similar for both FYM- and fertiliser-treated soils. However, the increase in CaCl<sub>2</sub> P was always much larger in the FYM-treated soil than in the soil that had fertiliser P (Johnston and Poulton, 2005; Table 11). The magnitude of the effect on CaCl<sub>2</sub> P seen in these experiments is likely to be larger than would be seen on many farms where FYM is used. This is because the amount of FYM used in the experiments was much larger than that often available for use on most farms. However, this is another example of the benefit from building up SOM. Animal slurry was not tested in these experiments so it is not possible to say whether similar effects would be seen where slurry rather than FYM is applied to soil. However, similar effects would only be expected if slurry produced a similar increase in SOM.

The FYM used in these experiments at Rothamsted and Woburn was made by bullocks fed mainly with hay and root crops produced on the farm. In this respect there could be an important difference between this type of FYM and FYM (or slurry) produced by an intensively managed dairy herd. Dairy herds are usually given supplementary feed containing added inorganic phosphates. Much of this inorganic P is excreted by the animal and would behave much as inorganic fertiliser P once added to soil (Steén, 2006). However there is evidence, again from Rothamsted experiments (Johnston and Poulton, 2005; Table 11) that when inorganic fertiliser P is added to soil with different levels of SOM then more P is extracted by CaCl<sub>2</sub> from soils with more SOM because of the low energy P bonding sites it contains.

### **3.3. Wastewater biosolids.**

The term biosolids, coined in America, is replacing the term sewage sludge. The latter can be considered a misnomer because it implies a sludge that has been settled out from sewage. In reality however, only about 60% of the material leaving the waste water treatment plant started out as suspended solids in sewage, the remaining 40% comprises biomass grown during the sewage treatment process (Evans, 1998). When added to soil, this microbial

biomass could behave quite differently to the original suspended material in sewage. However, the word sewage and where appropriate sewage sludge will be used in Section 3.3.1. that discusses early work.

### *3.3.1. Early work and experiments on the disposal of sewage.*

The disposal of human excrement is as ancient as human beings but it is only comparatively recently that there have been problems. Once humans began to live in small permanent settlements every family sought to provide its own food from its own plot of land, even in the Middle Ages when the 2- and 3-field system of cropping was practised. Human excrement, most probably as 'night soil', would have been added to the cultivated soil and most of the plant nutrients in the food were returned to where the crops were grown. The transport and use of night soil was a feature of Chinese agriculture until comparatively recently.

Problems began to increase as the urban conurbations expanded from the beginning of the Industrial Revolution. However, it was not just the rapidly increasing urban population that created the problem, rather it was the rapid expansion in the number of households with water closets. Flush toilets were not new, there is reference to their use in the about the 26<sup>th</sup> century BC, and in subsequent centuries. Elizabeth I of England is said not to have used 'The Ajax', forerunner of the modern flush toilet invented for her, because it made too much noise! In the late 1700s and early 1800s, a series of patents for improvements in the flush toilet were granted and having a flush toilet in a house was no longer a privilege of the rich. But flush toilets have to be connected to a sewerage system to remove the liquid and the suspended solids and when there are many of them, the sewerage system has to be extensive.

It is probable that initially, the sewers of London discharged directly into the River Thames; there are references to the stinking mudflats on the sloping, tidal parts of the lower Thames estuary at low tide. There is a brief mention by J. B. Lawes of 'sewage irrigation' for green crops in 1848 but it was not until 1852 that Lawes began to become more involved in discussions concerned with sewage. In 1852, he was asked his opinion about applying raw sewage to the Essex marshes. The reply he gave is not known but he certainly supported this method of disposing of sewage later, although some thousands of hectares of land would be required to do so! In 1857, Lawes was appointed a member of the Royal Commission on the Sewage of Towns. It was becoming apparent that 'measures for improved water supply and drainage (*in towns*) are retarded from the difficulties of disposing of the increased sewage which results from them'. Rapid, easy disposal was more important than any consideration of using the sewage. The Royal Commission suggested two methods of disposal. One was the application of whole (untreated) sewage to land, although grass was the only suitable crop. The other method was treatment of sewage by a chemical process to separate its most offensive portions. Adding lime was known to be effective but it caused

coagulation/precipitation and blocking of sewers, treatment later in the removal process had not then been considered.

In the early 1850s, Lawes and Gilbert (1855) reviewed published information on human diets, and the amounts of plant nutrients in them. They also reviewed published results on the amounts of faeces and urine produced by men, women and children and determined their nutrient content, many of these analyses were done at Rothamsted. The outcome of this exercise at that time was that each year the sewage from 2,500,030 persons living in London was estimated to contain about 19,111.744 t carbon, 9,006.149 t nitrogen, and 5,190.116 t phosphates (probably determined as tricalcium phosphate). In early publications like this one, Lawes and Gilbert were given to 'spurious accuracy', a facet of their published work that changed with time!

The Royal Commission decided that there was a need for experiments testing sewage and Lawes and Gilbert were involved in the design and execution of these experiments at a farm near Rugby between 1861 and 1864. The experiment was ambitious. There were three grass fields, each a little larger than 2 ha, and each divided into four to test a nil and three amounts of untreated sewage: 7,500, 15,000 and 22,500 t/ha each year, the total being applied in small amounts throughout the year. On one field the effect of the treatments on the yield of grass was recorded. On the second field, the grass was eaten by oxen, or it was cut and fed to the oxen, and the live-weight gain of the animals was recorded. On the third field, the grass was eaten by milking cows, or it was cut and fed to the cows, and the yield of milk and its composition were recorded. The results were given in great detail by Lawes and Way (1865). Put very simply there was a response to the untreated sewage, but the benefits were small. Lawes and Way reckoned that when untreated sewage was applied at about 12,500 t/ha per year, it was not worth more than  $\frac{3}{4}$  to  $\frac{1}{2}$  d per ton. In a later summary Lawes 'doubts whether a farmer could afford to pay even 2d per ton of sewage' (British pre-decimal coinage per imperial ton, about 0.01 €/t today without allowing for inflation!). Interestingly throughout the period of the experiments, a number of writers thought that Lawes was grossly underestimating the value of sewage. The suggestion was that if the 'true' value of sewage was made known, the sales of Lawes' manures would decrease and his profits from the business would decline! More importantly perhaps, Lawes and Way (1865) also noted that sewage could be applied continuously to land to avoid pollution of rivers and where local circumstances are favourable towns could apply their sewage in agriculture. They also considered that when applied to grass throughout the year at a total of 12,500 t/ha, the drainage could be discharged to rivers without harm to fish.

There is some evidence that Lawes was probably correct in the small value he gave to sewage. J. J. Mechi, a second generation immigrant, was a successful business man in London between 1830 and 1840. He made a considerable fortune from the 'magic razor strop', which bore his name, and was used to sharpen safety razor blades. He also patented a porcelain 'candle', which when

burned in a coal gas flame improved the brightness of the flame. In 1841, he purchased a farm of 53 hectares at Tiptree Heath, Essex, on an unproductive, heavy clay soil. He wrote much about English farming and how to make it productive. Many of his ideas came from his correspondence with Justus von Liebig in Germany. In the early 1860s, Liebig was railing about the scandal of London allowing its valuable sewage to be discharged to the sea, and Mechi seems to have accepted this. Mechi took up Liebig's ideas about the use of sewage, particularly the need to incorporate it deeply into the soil. It may be a little unfair to draw too many inferences, but Liebig's faithful disciple at Tiptree Farm had many poor harvests after 1866. These eventually lead to Mechi being declared bankrupt and his estate put into liquidation just before his death in 1880. According to the writer of Mechi's entry in the Oxford Dictionary of National Biography, he died of a broken heart when his farm failed.

But the real moral of this story is that good experiments are needed to test all aspects of the possible benefits and drawbacks of any product before it becomes widely used. This applies especially to materials introduced into agriculture where effects may not be manifest for many years and any adverse effect could be difficult to eradicate quickly.

I wonder whether Lawes and Gilbert contemplated having additional treatments in the sewage experiments at Rugby to compare the effects of sewage with those of NPK fertilisers. In reality doing this would probably have made the experiments too large for them to manage easily and one can understand why such additional treatments were not included. Today, however, it ought to be possible to not only design appropriate experiments but to undertake them.

Lawes' work on sewage closely followed the padlocking of the Broad Street pump by John Snow in 1854. Snow realised, before the discovery of the role of bacteria in the transmission of disease, the importance of preventing the contamination of drinking water by sewage. Thus, it is perhaps strange that the risks of spreading disease from sewage discharged on farmland were never mentioned in the period of Lawes' work on sewage. One can but marvel of the likely suffering of those engaged in the experiments at Rugby and wonder what might have happened if the application of untreated sewage to land had become the accepted method of disposal.

By the end of the 19<sup>th</sup> century, which coincided with Lawes' death, all sewage of towns was carried by water; a little was applied wet to land, much went to sea and the aeration of sewage had been started in order to produce an acceptable 'sludge'. A few years later the method of producing 'activated sludge', invented in Britain, became the standard for processing sewage from large towns.

### ***3.3.2. The Woburn Market Garden experiment.***

The use of biosolids as a soil amendment appears to have languished during much of the 20<sup>th</sup> century. There were exceptions in the UK during the 1<sup>st</sup> and

2<sup>nd</sup> World Wars when supplies of P and K, in particular, were restricted. The difficulty of handling a bulky material containing small concentrations of plant nutrients and the ready availability of inorganic fertilisers was largely responsible for the lack of interest in using biosolids.

It was not any possible benefits of any inorganic nutrients in biosolids that persuaded the Lawes Agricultural Trust to allow H. H. Mann, the Director in Charge of the Woburn Experimental Station, to include biosolids in an experiment he was keen to start at Woburn. The soil is a sandy loam and yields of most crops in the 1920s and 1930s were unacceptably poor. Yet the Farm is not far from that part of south Bedfordshire where very similar sandy loam soils are very productive. For many years this area was noted for producing large yields of vegetables for the London markets. At the start of the 2<sup>nd</sup> World War, Mann was keen to see whether the productivity of the soil at Woburn could be increased by the application of large amounts of biosolids and FYM. The Woburn Market Garden experiment was started in 1942 (Johnston and Wedderburn, 1975). There were four treatments, FYM, a vegetable compost (a compost of green material collected around the farm activated with FYM), biosolids and a compost of biosolids and straw. The biosolids used at Woburn came from the West Middlesex works at Mogden, Isleworth; and were an activated sludge taken mainly from the drying beds but including some 'activated and digested' sludge. When the experiment began the sewerage system with its outfall at Mogden, was collecting largely from domestic sources although later in the war and after, there may have been some sewage from industrial sources. The organic treatments were tested at 37.5 and 75 t/ha fresh material per year between 1943 and 1950 and then from 1951-1960 at 25 and 50 t/ha fresh material applied for each of the three crops grown in each two-year period. There was a treatment without organic manures and all plots had a small annual application of P and K as fertilisers. Horticultural crops were grown and briefly the yields of all were increased by the manures tested (Mann and Patterson, 1963; Johnston and Wedderburn, 1975).

#### 3.3.2.1. Recycling phosphorus through organic manures.

Of more relevance in relation to the topic of this paper and this Conference is the recycling of P through the manures and to some extent this must be linked with changes in SOM. Changes in SOM are important in relation to the ability of organic matter to provide low energy bonding sites able to retain P in soil. Samples of all the organic manures applied in the Woburn Market Garden experiment were archived and the amounts of organic matter and nutrients added can be calculated. Unfortunately no samples of the crops grown were either analysed or saved and so it has not been possible to prepare nutrient balances. Adding such large amounts of manure over a period of 18 years added large amounts of organic matter; 100 and 200 t/ha where FYM was applied at the single and double rates and 160 and 320 t/ha with biosolids. In 1960, there was a linear relationship between the amounts of organic matter added in the four organic manures and the amounts of organic carbon in soil (Johnston, Poulton and Coleman, 2009). However by 1960, only about 30-35% of the added organic matter was still in the soil (Table 1, overleaf). Recycling

organic manures comes with a cost. While a similar amount of carbon (C) would have been lost wherever the original material had decomposed, there seems to be a belief that when added to soil, organic manures go on increasing the level of SOM. But as these data show this is not so; there will be a loss of C, mostly as carbon dioxide, when organic manures are added to soil and the loss will be considerable as the level of SOM reaches the equilibrium level for each soil type and the farming system practised.

**Table 1:** *Amounts of organic matter and phosphorus added in farmyard manure and biosolids, and the retention of organic matter and total phosphorus in the surface 23 cm soil and the increase in Olsen P, Woburn Market Garden experiment, 1942-1960 (adapted from Johnston, 1975).*

			Fertiliser		Biosolids	
			1 <sup>a</sup>	2 <sup>b</sup>	1 <sup>a</sup>	2 <sup>b</sup>
Amount of organic matter added	t/ha <sup>c</sup>	0	100	200	160	320
Extra organic matter in soil	t/ha		30	64	57	109
% added organic matter retained	%		30	32	36	34
Total P	mg/kg	1095	1440	1755	2070	2990
Increase in total P	mg/kg		345	660	975	1895
Total P	kg/ha <sup>d</sup>	3760	4950	6040	7120	10280
Increase in total P	kg/ha		1190	2280	3360	6520
Total P applied, in organic manure	kg/ha		2570	5140	5950	11900
% total P retained in top 23 cm soil	%		46	44	56	55
Olsen P	mg/kg	94	140	183	125	158
Olsen P	kg/ha <sup>d</sup>	320	480	630	430	540
Increase in Olsen P	kg/ha		160	310	110	220
Increase in Olsen P as % increase in total P	%		13	14	3	3

<sup>a</sup> Single rate of addition.

<sup>b</sup> Double rate of addition.

<sup>c</sup> Estimated as total dry matter in fresh manure *minus* the ash.  
Organic matter equals %C x 1.72.

<sup>d</sup> Based on a soil weight of 3,440 t/ha.

Total and Olsen P were determined in the 0-23 cm depth of soil from all plots in autumn 1960 (Table 1). In the 18-year period during which biosolids and FYM were compared very large amounts of P were applied. There was a linear relationship between the P added and the total P in the soil which accounted for 94% of the variance (Johnston, 1975). Soils treated with FYM and vegetable compost were on the lower side of the fitted line because it was with these two treatments that more of the added P had moved out of the

surface soil. Table 1 shows that between 44 and 56% of the added P could be accounted for by the increase in total P in the surface 23 cm topsoil. The P removed in the harvested crops would account for some, but certainly not all of the 'missing' P. Some P may have been moved below 23 cm and some may have been lost by surface runoff. However, the result would suggest that smaller amounts of P should be applied than those tested here to minimise the amount of P that cannot be accounted for.

The relationship between total P applied by 1960 and Olsen P in the top 23 cm soil in 1960 was very revealing. More of the added P remained as readily plant-available Olsen P on plots given FYM and vegetable compost than on plots given biosolids and biosolids/straw compost (Table 1). That 13-14% of the increase in total soil P remained as Olsen P where FYM or vegetable compost was applied was very similar to the proportion found for other sandy loam soils at Woburn and the silty clay loam soil at Rothamsted (Johnston, 2001). A very much smaller proportion of the increase in total P remained as Olsen P (~3%) on plots treated with biosolids and biosolids/straw compost. This can be explained by the treatment at the sewage works. In the early 1940s, Jenkins and Lockett (1943) estimated that as much as 40-60% of the total P in crude sewage entering treatment works was discharged as effluent to rivers in the UK. Thus, it is very probable that much of the P in sewage entering the Mogden works, from which the biosolids used in this experiment came, would have been lost as water-soluble P. Consequently, a large proportion of the P in the biosolids and the biosolids/straw compost would have been very stable organic P or recalcitrant inorganic P, and these sources of P would have become readily plant-available only slowly. In this particular experiment although such a very small proportion of the added P contributed to the Olsen P pool, the amount of P added was so large that the Olsen P increased to more than 120 mg/kg, far in excess of crop requirement. The very large amount of FYM and vegetable compost added also increased Olsen to more than 140 mg/kg by 1960. Clearly the amount of any manure added should be adjusted to maintain soil P at or about the target Index (see Section 5).

The very large amounts of water-soluble, bio-available P that could be discharged to rivers in effluent from sewage treatment works where the sewage was anaerobically digested led to a deterioration of water quality in many rivers from the 1970s. This led to steps being taken to limit P discharges from larger treatment works by adding chemical salts to precipitate various P-containing compounds.

#### 3.3.2.2. Additions of heavy metals.

Applications of biosolids and biosolids/straw compost in the Woburn Market Garden experiment were discontinued after 1961. This was because evidence from both crop and soil analysis showed there was an increase in plant-available heavy metals in the soils where these treatments had been applied (Le Riche, 1968). Little at that time was known about the relationship between the concentration of these metals in plants and the risk to human health.

Although the plots continued to be used to test P and K fertilisers all the produce was destroyed after yields were taken. McGrath (1984) analysed the archived samples of the organic manures for their heavy metal content. The concentration of cadmium (Cd) had increased from 40 to 120 mg Cd/kg biosolids dry matter during the period 1942 to 1961. Based on this concentration of Cd in dry matter, if 37.5 t/ha of fresh biosolids at 56% dry matter and 120 mg Cd/kg dry matter had been applied then 2,520 g Cd would have also been added to the soil. A similar calculation can also be done for FYM. Based on the concentration of Cd in FYM found in this experiment; if 37.5 t/ha fresh weight FYM with 26% dry matter and 1.8 mg Cd/g, had been applied, 18 g Cd/ha would have been added to the soil.

Following the cessation of the experiment growing market garden crops, various other crops, including *Trifolium repens*, were grown. The growth and yield of the clover were much decreased when grown on the plots that had received biosolids and biosolids/straw compost (McGrath, Brookes and Giller, 1988). The decrease in yield was associated with much less N in the plant tissue and the large concentration of heavy metals in these soils was thought to be having an adverse effect on microbial N fixation in the nodules. It was also thought that heavy metals might affect the function of a range of microbial processes in soil. However, Johnston and Poulton (2005) in a study on the decline in soil organic matter, could find no evidence for a difference in the rate of microbial decomposition of SOM in the differently treated soils with differences in the concentration of heavy metals. Applications of the four different organic manures, each at two rates, built up eight different levels of SOM (Johnston, 1975). There were no applications of biosolids and biosolids/straw compost after 1961 and of FYM and vegetable compost after 1967. A range of crops was grown and the soils were periodically sampled to monitor the decline in SOM. The eight individual SOM decline curves could be brought into coincidence to produce a unified decay curve (Johnston and Poulton, 2005; Figure 2). This was strong evidence that the microbial population on the biosolids-treated plots were decomposing SOM at the same rate as on plots containing much smaller concentrations of heavy metals. Thus the adverse effects of heavy metals on N-fixing bacteria seem to be specific to that group of organisms.

#### **4. TWO WASTE MATERIALS AND AN UNEXPECTED BENEFIT.**

Following the Second World War, the Forestry Commission envisaged a large-scale programme of afforestation and this required the production of large numbers of transplants for planting out in the forests that were to be established. In England it had become standard practice in nurseries producing seedlings and transplants to use composts to encourage the development of mycorrhizal associations with young developing roots. Such associations increased nutrient uptake from what were, in many cases, nutrient-poor soils. Research on the nutrient requirements of the plants produced in production nurseries was started in 1945 under the direction of

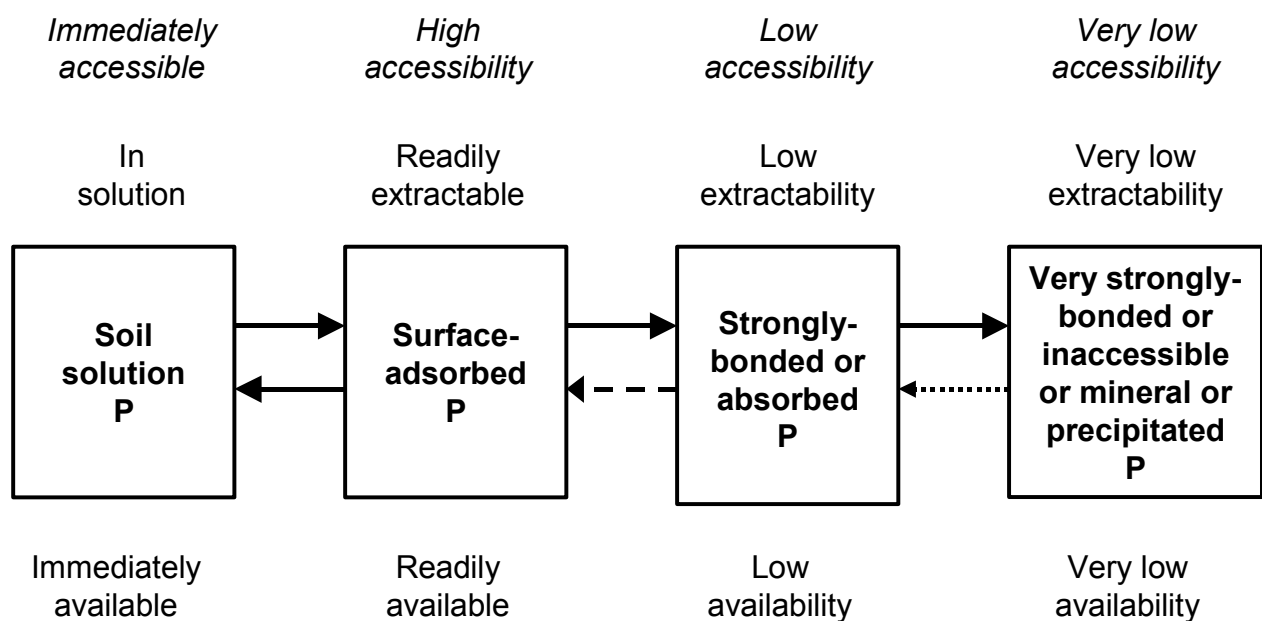
E. M. Crowther (Rothamsted Experimental Station). It was quickly shown that growth could be increased by the use of fertilisers. Then in 1949 at the Wareham nursery of the Forestry Commission, and sporadically in subsequent years, Sitka spruce seedlings grown on many plots were observed to have withered needle tips close to the growing point – a symptom referred as needle tip-burn. The only treatment with few or no symptoms was that given the standard compost used at that nursery. This compost was made from spent hops (hopwaste), an industrial waste from the local brewery in Wareham, and bracken, an invasive weed growing on poor soils. The contrast between fertiliser-grown seedlings suffering tip-burn and compost-grown seedlings free from damage caused some observers to wonder whether there was some special organic effect. Eventually it was shown that tip-burn was caused by copper (Cu) deficiency. The Cu content of bracken was about 10 mg/kg and of the un-extracted hops was about 95 mg/kg. The hopwaste however, contained about 1000 mg/kg Cu. The inference was that the large concentration of Cu in the hopwaste probably came from the copper installations in the brewery and copper from different surfaces was strongly bound to the organic matter. As the hopwaste in the compost was mineralised by microbial action in the soil, the Cu was released and was available for uptake by the roots of the Sitka seedlings. It was subsequently shown that applying Cu with the NPK fertilisers was equally effective in preventing needle tip-burn (Benzian, 1965).

## 5. EFFICIENCY OF PHOSPHORUS USE IN AGRICULTURE.

Concern about the life span of world P resources has been associated with the apparent inefficiency with which P is used in crop production. Frequently it is stated that the efficiency of P use is only 10-15% and at best rarely exceeds 25%. If this is correct, and large amounts of P are applied because of inefficiencies in its use, then known P resources are likely to last less time than many people have predicted. Syers, Johnston and Curtin (2008) have recently reviewed evidence for the efficiency of soil and fertiliser phosphorus use. The review has challenged long-held, conventional thinking on the practical implications of the reactions of P in soil. Importantly it has sought to discard once and for all, the belief that P added to soil and not used by a crop becomes irreversibly fixed in soil. The review provides evidence that on a wide range of soil types throughout the world, P use efficiency is often 60-70% and can be as large as 90% provided that the right method of assessment and an appropriate time scale are used. These authors came to their conclusions from an assessment of changing concepts about the behaviour of P in soil, irrespective of its source, and they successfully reconciled the new concepts of P behaviour that they put forward with available agronomic information.

One important outcome of the review has been to further develop ideas about the plant-availability of soil P that were suggested by Johnston (2001). The current concept is that inorganic P is retained (sorbed) by soil components with a continuum of bonding energies. A consequence of this is that sorbed P

will have varying extractability related to the nature of its physical association with the soil components on which the P is retained. If P is held with a range of bonding energies, its extractability both by plant roots and by chemical reagents will also vary but both could be related one to the other. Thus soil P can be characterised in terms of its availability to plants. These descriptions are essentially operational definitions and relate to the ability to characterise them by chemical extractants suitable for use in routine advisory work. Reagents used in routine soil tests extract different amounts of P but measure P that is in the soil solution and in a pool of P that is readily available for crop uptake – the readily available pool. Thus, no particular type of P is extracted but this is not important. What is important is that there should be a strong relationship between the amount of P extracted and the response of a crop to either soil P or to an application of fresh P. When this strong relationship exists then the soil P that is extracted can be thought of as being reasonably well defined in terms of the availability of the P for uptake by crops. This concept can be conceptualised and expressed diagrammatically as in Figure 1 in which soil P is represented as being in four pools. The P in each pool can be defined in relation to the way in which it is retained in the soil, to its availability for uptake by plant roots and to its extractability by chemical reagents.



**Figure 1:** *Conceptual diagram for the forms of inorganic P in soils categorised in terms of accessibility, extractability and plant availability.*

The most important concept illustrated in Figure 1 is the reversible transfer of P between the first three pools. The release from the fourth pool is very slow, often over decades. Evidence for reversible transfer of P between pools comes from yields and P uptakes by crops grown in long-term field experiments and from sequential extraction of soil P in soil samples from such experiments; the review presents such evidence. It is with this knowledge of the reversible transfer of P between the pools that current thinking about the behaviour of P

in soil is fundamentally different from the belief that P is irreversibly fixed in soil. The transfer of P between pools, when P is added to soil in fertilisers and manures or removed from soil when there is no addition of P, cannot be reconciled with the idea of irreversible fixation of P.

When a fertiliser or manure containing water-soluble P is added to soil a very small proportion remains in the soil solution and a small part may undergo initial precipitation reactions in some calcareous soils. However, the majority of the P rapidly becomes distributed between the readily-available and less readily-available pools by processes of adsorption and then absorption. In England, Wales and Northern Ireland, the readily-available pool of soil P is estimated using either Olsen's method (Olsen P) or an anion exchange method (resin P) (MAFF, 2000). Using the behaviour of soil P as discussed above, it is possible to develop a concept of a critical level for readily plant-available soil P, which may vary with soil type and farming system. But maintaining soil at the appropriate critical level – the target Index - greatly increases the opportunity to achieve optimum economic yields and maximise the benefits from other inputs required for a crop to grow well. There are good prospects that adopting the approach of using critical levels and maintaining a soil at the appropriate P Index, will improve the efficiency of P use in agriculture because soil will not be over enriched with P by adding more than is required to grow good crops. Recycled P will play an important role in maintaining plant-available P at the critical level.

## **6. POSSIBLE SCENARIOS FOR IMPROVING PHOSPHORUS RECYCLING.**

Recycling any waste, whether or not it is treated in some way, will depend on a number of factors. Waste derived materials must have benefit to agriculture, must be acceptability to the public with no perception of any risk from their use, and their use must be financially viable and environmentally acceptable. The last of these four factors is becoming increasingly important, the more so for those people who have ready access to food at reasonable cost. A number of these topics are discussed in more detail in other papers presented at this Conference.

Improving the efficiency of soil and fertiliser P use will most probably help to conserve the world's global reserves and resources of P. Section 5, above, briefly mentions the concept of maintaining soils at a target Index for plant-available P. This concept is based on results from field experiments in which it was shown that as plant-available P in soil increased, yields increased to reach a maximum at a certain level of plant-available P (the critical level or target P Index), and did not increase further as more P was applied. Examples of critical levels of Olsen P are given by Syers, Johnston and Curtin (2008), and by Johnston and Syers (2006) The effect of SOM on the critical level of Olsen P is discussed by Johnston and Poulton (2005). The importance of recycled P will depend on it being able to maintain the appropriate critical P level for the soil and farming system.

## 6.1. Phosphorus recycled through biosolids and farm-derived organic manures.

In a recent review, White and Hammond (2007) have updated the data on the total P loads (TP) to the waters of England, Wales and Scotland. They estimate a total P load of 41,600 t P per year. In this total load the following four sources make approximate contributions of: 60.7% from households (i.e. from sewage treatment works, presumably smaller works without tertiary treatment), 28.3% from agriculture, 4.6% from industry and 6.5% from background sources. The 60.7% of the total P load to rivers from households is about 25,300 t P which is about 25% of the total application of  $P_2O_5$  in fertilisers in 2006/07. Recycling this amount of P or a large proportion of it to UK agriculture would represent an appreciable saving in P use in the UK. Similarly, the review estimates that 28.3% of the total P load in rivers comes from land, including from eroded soils (and river banks) and surface run-off from applied slurries etc. This equates to about 12% of the  $P_2O_5$  applied in 2006/07 as fertiliser. It would be impossible to prevent all this P being transferred to rivers. But if that fraction of the P lost by overland flow as a result of applying slurry when soil and weather conditions are not suitable could be prevented, then much P would be saved. Combined savings in P use by recycling P in biosolids and minimising losses from land would make a positive contribution to saving global P reserves. The direct economic benefits to the farmer in using recycled P would depend on the relative cost of 1 kg  $P_2O_5$  as fertiliser and as recycled P. It would also be important to know how the cost of doing the recycling would be met.

### 6.1.1. Recycling phosphorus through biosolids.

The two end-products at sewage treatment works are the solid and the liquid. The liquid effluent contains water-soluble inorganic P and low-molecular weight organic P and both are bio-available. It is this fraction of P that creates problems associated with eutrophication in rivers. Currently this P can be removed by adding salts of calcium, iron or aluminium. There are conflicting results about the availability of this precipitated P to plants. Iron and aluminium phosphates may 'age' and with time the phosphate in these compounds may become less available for uptake by roots. Further work to show the availability of such P compounds under different conditions and time scales would be justified. In the absence of any chemical addition to the sewage sludge used at Woburn in the Market Garden experiment only a very small proportion of the large amount of total P added was present as Olsen P (see Section 3.2.2.1. above).

Balmér (2006) discussed in detail ways of removing P from municipal waste water. This will not be discussed further here except to note that without any treatment, P is sometimes precipitated from waste-water streams as struvites, for example, magnesium ammonium phosphate, and this can be achieved by adding appropriate salts to the water effluent. Johnston and Richards (2003) showed that the P in struvites is as available to plants as the P in triple superphosphate. So this could be a useful way of removing P from the effluent

from sewage treatment works, thus minimising the risk of P being transferred to rivers, while at the same time recycling P for use in agriculture in a form that is as available to plants as the P in superphosphates.

The addition to agricultural soils of heavy metals in biosolids is mentioned in Section 3.3.2.2. I consider that much credit goes to the water authorities in minimising this risk by identifying point sources and removing them. As a result of concern about the effects of these heavy metals on human health if they enter the food chain, much work has been done to determine risk and appropriate measures put in place to minimise risk from the application of heavy metals in biosolids. Codes of practice for the use of biosolids in agriculture are available from Defra (1996) and there are guidelines for the use of biosolids in agriculture from ADAS/WaterUK (2000).

Recently, there has been an increased awareness of possible contaminants in biosolids from food supplements and proprietary medicines sold by chemists for human consumption. The number of food supplements is very large, recently, for example in Italy, Sequi (2003) found about 600 food supplements that contained chromium. Presumably most of this chromium, together with other metals present in food supplements will be found in biosolids. There is also an issue of organic pollutants in biosolids and this is discussed by Vinnerås (2008, this Conference). While work has been done on the effect of heavy metals on soil microorganisms, the effect of organic pollutants on this important living population of organisms in soil needs to be considered also. This is an area where further research is needed.

Section 3.3.1 describes early work on the disposal of untreated sewage to land, and mentions John Snow and the Broad Street pump. In 1854, there was an outbreak of cholera in the Soho district of London, in and around Broad Street. John Snow's pioneering data analysis proved his hypothesis that cholera was spread by drinking-water. Snow carefully mapped the distribution of cholera cases and found they were distributed in a tight cluster round a water pump located in Broad Street. Microscopic examination of a water sample from the pump showed a bacteria Snow had not seen before, and he guessed that it was this bacteria that caused cholera. On removing the pump handle so that local residents could not get the water from this shallow well, the cholera outbreak stopped almost immediately. The water in this and other shallow wells in the London area was contaminated by sewage. Future use of any recycled material must always be seen to have no health hazard and, nowadays, minimum environmental risk.

However, certainty about health risks is not the whole problem, the public must perceive that there is no risk in the use of any material added to the soil that is used to produce food. The confidence that the public has in the food supply is of paramount importance in influencing what it chooses to eat and from where it will purchase its food (Hall and Jones, 1999). For example, consider the initial effect of BSE on beef sales. Another example some years ago is the decision not to publish a short article about the use of biosolids on sugar beet. It was not published in case the public became aware that the beet

from which the sugar was extracted had been grown on soil treated with biosolids. The fear was that consumers might not buy manufactured food containing such sugar. Again within the last few months a programme on UK TV first showed well-composted biosolids being applied to land to recycle organic matter. A few shots later showed interviews with shoppers in London. They were horrified to learn that food might be produced with, as they said, 'human poo'. Few people know sufficient about plant nutrition to realise that the use of biosolids is carefully controlled, presents little risk to human health and a great opportunity to recycle nutrients and organic matter. Public perception and acceptability can easily become a major obstacle to using recycled materials.

### ***6.1.2. Recycling phosphorus through farmyard manures.***

Long-term experiments at Rothamsted have shown that P added to the silty clay loam at Rothamsted, the sandy loam at Woburn and the sandy clay loam at Saxmundham behaves as P added in fertilisers in its effect on increasing the readily plant-available P (Olsen P) in soil. It is most probable that the P in farmyard manures and fertilisers would behave similarly on other soil types. The major problem is not with the efficiency of recycling but with the more difficult problem of excess manure production in some regions/localities with too little land to use it on to maximum benefit. The possibility of moving manure from areas with excess to areas where it could be used with benefit are discussed by Fealy (2008, this Conference).

### ***6.1.3. Other organic wastes.***

There are many other organic wastes that could be used with benefit in agriculture and some of these are discussed in detail at this Conference, for example, Graziano *et al.* (2008, this Conference). To some extent the need to use these wastes is driven by the need to lessen the amount of material going to landfill. However, even the return of small amounts of nutrients could offer a saving in P use. Such materials include household green waste and vegetable waste generated during the preparation of vegetables for sale as 'prepack'. The composting process has been described by Lopez-Real (1990), the opportunities for recycling nutrients through composts by Searle (1993), and the effect of compost production on carbon and nitrogen cycles by Bernal (2008, this Conference).

### ***6.1.4. A downside of recycling organic manures.***

Much recent discussion on the use of organic manures in agriculture has been directed towards increasing the level of organic matter in soil, rather than recycling plant nutrients. However, this is not necessarily a win-win situation. SOM does not go on increasing indefinitely, a point not appreciated in a number of recent papers on SOM (Bellamy, *et al.*, 2005; Khan, *et al.*, 2007). SOM reaches an equilibrium level which depends on the farming system and hence the input of organic matter, the rate at which added organic matter and existing SOM breaks down, soil type and climate (Johnston and Poulton, 2005; Johnston, Poulton and Coleman, 2009). Adding large amounts of organic materials will increase SOM, but once the equilibrium level has been reached,

the rate of loss of soil carbon will equal the rate of addition of carbon in freshly added organic matter. As SOM approaches the equilibrium level the amount of carbon lost as carbon dioxide can be considerable. Thus while organic wastes will increase SOM and recycle nutrients, there may be a limit to the amount of organic matter that can be accumulated and possible restrictions on the amount of P that can be added may limit the application of organic manures.

## **6.2. Integrated plant nutrient management.**

The principles of integrated nutrient management (INM) seek to ensure that all nutrients are used efficiently in crop production (Van Erp and Oenema, 1993; Törner and Drummond, 1999; Aulakh and Grant, 2007; Sjöström, 2008, this Conference). The three main sources from which crops acquire nutrients are the soil, livestock manures and other wastes, and manufactured fertilisers. When deciding on the amount of fertiliser to apply the first consideration is to decide the amount of each nutrient required to achieve the optimum economic yield; then how this nutrient demand can be met. First there is the quantity available from the supply already in the soil and to this should be added the amount that could be supplied by the application of any available organic manure. If the nutrient supply from these two sources is not sufficient for the estimated needs of the crop, the balance can be applied as fertiliser. Integrated nutrient management for P is to some extent simplified because the aim is to maintain the soil at the appropriate P Index (Section 5), and P in organic manures can contribute to this. The availability of nutrients in some organic wastes is the topic of this Conference and is discussed by Evans (2008, this Conference) and Hartung (2008, this Conference).

Data from the British Survey of Fertiliser Practice show that few arable farmers make any allowance for the nutrients in any organic manure they apply when assessing how much fertiliser to apply. Thus such farmers could be considered to not practice INM. That farmers do not allow for the nutrients in organic manures is a little surprising in view of the fact that data for the average nutrient content and nutrient availability in a range of organic manures is given in RB209 (MAFF, 2000). Farmers can therefore, if they wish, make allowance for the nutrients in organic manures and there is no obvious reason why they do not do so.

## **7. ENVIRONMENTAL AND OTHER ASPECTS OF RECYCLING.**

At the IFS Cambridge Conference in 1993, O'Riordan (1993) noted that the UN Conference on Environment and Development held in Rio de Janeiro in 1992 produced an action plan for sustainable development known as Agenda 21. The Rio Conference created a UN Commission on Sustainable Development with the purpose of receiving and reviewing national strategies for sustainable development. In addition, the Fifth Environmental Action Plan of the European Community requires that sustainable growth be incorporated into all sector policies. Along with industry, agriculture has a special place in this

process, but unlike industry, agriculture is involved in complex biological systems that are impacted by, and have an impact on, many other systems that are external to agriculture. O'Riordan also noted that sustainability when applied to agriculture had implications for science and economics and how current agricultural policies were evolving so that they were having both a social and environmental impact on agriculture.

Recycling any material to agriculture must consider the wider environmental implications of doing so and the energy involved in the recycling process. The impact of nutrient use and management on various aspects of the environment have been discussed by Pettersson (1993), Powlson (1997) and Parris and Reille (1999). European and UK regulatory requirements for waste product application to land are discussed by Davis (2008, this Conference).

Recently Schröder and Bos (2008) have discussed the relationships between nutrient recycling, environmental impacts and agricultural production. They looked at the increasing pressure on the natural world and the environment as policy makers want agriculture to produce substitutes for fossil fuels as well as food. They pointed out that annual production of food, feed-stocks (i.e. animal feed, bioenergy, fibre and other raw materials), biodiversity (i.e. food for wildlife) and sequestered carbon (i.e. carbon in above ground biomass or soil organic matter) are interrelated. As a result, an expansion of one compartment will invariably be at the expense of another and somehow and at some time choice has to be made. In this respect a recent quotation from 'Problems are inevitable – Problems are soluble' by Professor David Deutsch of the University of Oxford is appropriate. 'The world is abuzz with plans to cut emissions at all costs. It ought to be abuzz with plans to cool the planet. Or to thrive on a warmer one. And not at all costs but efficiently'. This quotation was used by Dawson (2008) in a paper that looked briefly at the development of agriculture in the UK and at the increasingly efficient use of energy in food production. The use of fossil fuel in agriculture is small and unavoidable compared to that of other industries. Whilst it should not be forgotten that agriculture generates edible energy far exceeding its use of fossil energy, some of this energy, in one form or another will be required to recycle nutrients.

Among other aspects not only of recycling, but also of the manufacture of fertilisers that have become important recently, has been the use of energy and life cycle analysis. So far most discussion about energy use has been within the manufacturing sector (Jenssen and Kongshaug, 2003). Pallière and Brentrup (2008, this Conference) have discussed energy use efficiency and greenhouse gas emissions in European N fertiliser manufacture, while Corré, Schröder and Verhagen (2003) compared energy use in conventional and organic farming systems. Future work needs to look at energy use in recycling of nutrients. Life cycle analysis has been discussed by Cowell and Clift (1995), Küsters (1999) and Janetos and Wagener (2001). In The Netherlands, McDonough and Braungart have recently been developing a concept called 'C2C – cradle to cradle'. This is an extension of the 'cradle to grave' concept in which an analysis of a process from a starting point to a final end product is

the focus of interest. The C2C concept includes consideration of recycling of the end product when it no longer serves its initial purpose. When applied to fertilisers this concept would involve not only using the nutrients in fertilisers efficiently but would seek to ensure that those nutrients removed in harvested produce are returned to the soil for further use in food production. This would appear to be an opportunity for putting into a formal framework and some sort of cyclic diagram what has been considered as recycling through manures and biosolids. The essential features that would be required in such a diagram would be amounts and energy relationships. It will be interesting to see how this concept develops further.

## 8. LOOKING TO THE FUTURE.

Sequi *et al.* (2007) noted that radical changes in food chains have broken traditional nutrient cycles. Consequently any legislative rules about nutrient use and recycling must not be limited to agricultural practice, but must be extended to take into consideration structural changes in all human activities in order to be effective. Waste resources are usually organic materials and can supply both nutrients and organic matter but such amendments do not always fit the needs of modern agriculture and too often their use has been ignored. To recycle nutrients, therefore, agriculture may need to readapt itself to use organic amendments effectively and efficiently where appropriate. However, there is increasingly rigid legislative constraints on the use of many organic amendments, especially biosolids, that seek to protect soil in particular and the environment in general. Such constraints sometimes appear irrational, partly because policy makers in different countries interpret the results of experiments in different ways even when the results are consistent. When experimental results differ, often for good reasons, this adds further to differences in interpretation of the data and often different or conflicting legislation. For example, there are often great differences between countries in the maximum allowable levels of undesirable substances or elements in organic wastes to be applied to soil. The limited scientific reliability of legislative rules is illustrated by comparing some rules established by the Environment Protection Agency of the United States (US EPA) and those already decided or under consideration by EC countries. For example, for biosolids to be applied to agricultural soils in the EC, the upper limit for zinc is 2,000 to 3,000 mg Zn/kg soil and for dioxins some hundreds of nanograms while the US EPA has established a cautionary limit of 7,000 mg Zn/kg and does not consider dioxins for all biosolids.

Hilton (2006) observed very similar differences between the rules adopted by the US EPA and other countries for the disposal of phosphogypsum (PG), the 'waste' containing radionuclides produced in the manufacture of phosphoric acid. Five tonnes of PG are produced for every one tonne of phosphoric acid, and in many parts of the world very large quantities of PG have been stacked on land or dumped at sea. This policy of stacking PG is under pressure for

reasons of cost, safety and environmental impact, and there are environmental issues about dumping it at sea.

Hilton (personal communication), as a result of his review of the different rules for disposing of PG, concluded that there are many reasons for taking a new look at regulatory policies and objectives that impact on the disposal of materials currently classified as wastes. These include dumping in landfill sites and stacking of PG. However, the producers of 'waste' rarely see an opportunity to use 'their' waste effectively. Bailey (2008, this Conference) puts forward an approach to help solve this particular problem. Hilton suggests that what is required is a positive attitude to waste prevention within strict guidelines for the safe use of wastes that will help to conserve both materials and energy, a win-win situation. It could also ensure that there is no transfer of 'legacy waste' from one generation to another.

Hilton (personal communication) has developed a concept of 'constructive regulation' for the use of secondary materials and co-products, such that they are not automatically considered as wastes, but rather a use is found for them. Together with this idea of constructive regulation there is also the concept of a 'social contract'. The future requirement will be for 'constructive legislation' to ensure that all countries treat each secondary product or waste material in a coherent and consistent way. To achieve this will require collaboration between regulators, producers and users to develop four core values:

- sustainability,
- coherence,
- consistency, and
- evidence.

At the operational level there will be four principle objectives:

1. Knowledge-based planning and operations.
2. A whole life-cycle management approach.
3. Stakeholder and public participation.
4. Pursuit of the public good.

There should be three main outcomes from such an approach:

1. Best practices.
2. Transparency and corporate social responsibility.
3. Evidence-based regulation and oversight.

In its widest sense, agriculture and food production should be encouraged to embrace such a concept.

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## OTHER PROCEEDINGS FROM THE CONFERENCE.

- 631 *Compost: production, use and impact on carbon and nitrogen cycles*, M P Bernal.
- 632 *Anaerobic digestion of farm manures and other products for energy recovery and nutrient recycling*, J Morgan and B F Pain
- 633 *Sustainability of biofuel production*, W J Corré.
- 634 *Marine algal biomass for energy generation and possible phosphorus recovery*, W A Brandenburg, B L Smit and J J Neeteson
- 635 *Nutrient and carbon recovery from household and food biowastes*, T D Evans.
- 636 *Industrial Symbiosis: Nationally co-ordinated by-product use and nutrient recycling*, M R Bailey, P D Jensen, H Hitchman and A Gadd.
- 637 *European policies to encourage integrated nutrient management and recycling*, Å E Sjöström.  
*European and UK regulatory requirements for waste product application to land*, M Davis.
- 638 *Phosphorus balances, fluxes, pathways and sinks in Europe*, I R Richards and C J Dawson.
- 639 *Energy use efficiency and GHG emissions in European nitrogen fertiliser production and use*, C Pallière and F Brentrup.
- 640 *Non-metallic contaminants in domestic waste, wastewater and manures: constraints to agricultural use?* B Vinnerås, J Clemens and M Winker.
- 641 *Plant nutrients from organic industrial by-products*, P L Graziano, R Calzavara, M Perelli and G Roccuzzo.
- 642 *Energy use and nutrient values in relation to manure transport distances*, R Fealy.
- 643 *Advances in nutrient measurement and treatment of farm manures and their application to land*, E Hartung.