

## MANAGING SOILS FOR BETTER PASTURES:

# FERTILISERS AND THE ENVIRONMENT

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*Abstract: The chemistry of nitrogen and phosphorus fertilisers are discussed in some detail in order to understand their role in the environment. Eutrophication and acidification are examined to elucidate the causes and establish links with farming and fertiliser practices. Cadmium is examined in detail because it is a heavy metal dangerous to health, and phosphate fertiliser is the main source. It can generally be said that except on very sandy soils, sensible fertiliser use should seldom present a threat to the environment. By contrast, withholding fertiliser may lead to erosion if plant cover is reduced.*

## INTRODUCTION

The use of fertilisers to boost pasture productivity is now an essential part in increasing productive capacity in any enterprise involving grazing animals. The main fertilisers are those containing phosphorus and nitrogen, although on some soils or where hay and silage are made, potassium may also be used.

Sensible use of these fertilisers at normal rates has not normally presented any hazards to the environment. However, under certain conditions (*ie.* drainage to ground water on very sandy soils), there has been pollution of the environment by fertilisers. This paper looks at the fate of fertilisers applied to pasture and discusses the problems which may occur.

## CHEMISTRY OF FERTILISERS APPLIED TO SOILS

### NITROGEN

In many agricultural systems (but not commonly in Australia or New Zealand), major inputs of nitrogen fertilisers are used to supply most of the nitrogen needed by plants. Fertiliser nitrogen interacts with soil components through biological and chemical processes, and soon after their application to the soil, most nitrogen compounds cannot be found in the form in which they were applied. An understanding of: (1) the reactions of nitrogen in the soil; (2) the sources of nitrogen for plant growth other than fertiliser; and, (3) the pathways for loss of nitrogen from the system, is needed in the development of sound farm management programs.

Here we will consider, in a general way, the amounts and forms of nitrogen in the environment and how these are affected by the use of nitrogen fertilisers.

On farmed land, most of the nitrogen is in the soil organic matter. This contains 2000 to 12000 kg N/ha. This

nitrogen is not normally available to plants. The amount of soil inorganic nitrogen [ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ )], which is the fraction that is immediately available to plants, will vary greatly depending on the time of the year, the fertiliser treatment, and properties of the soil, but it is seldom greater than about 100 kg N/ha. In a soil which has not received nitrogen fertiliser, it is usually less than 50 kg N/ha.

### Forms and transformations of nitrogen

Gaseous forms of nitrogen in the soil atmosphere and dissolved in the soil solution include: elemental nitrogen ( $\text{N}_2$ ); nitrous oxide ( $\text{N}_2\text{O}$ ); and, ammonia ( $\text{NH}_3$ ). Inorganic forms are: ammonium ( $\text{NH}_4^+$ ); nitrite ( $\text{NO}_2^-$ ); and, nitrate ( $\text{NO}_3^-$ ). Nitrate and nitrite exist entirely as ions in soil solution while most of the ammonium exists in exchangeable and clay-fixed forms and very little is in the soil solution. Organic nitrogen in soil organic matter exists in highly complex, poorly defined compounds.

The important physical, chemical and biochemical reactions occurring in the nitrogen cycle are listed below:

The processes involved are as follows:

1. **Mineralisation:** the microbial conversion of organic forms of nitrogen to inorganic forms (organic matter or urea to ammonia).
2. **Immobilisation:** the assimilation of inorganic forms of nitrogen by plants and micro-organisms to organic forms.
3. **Nitrification:** the microbial oxidation of ammonium to nitrate.
4. **Denitrification:** the bacterial reduction of nitrite or nitrate to nitrous oxide and elemental nitrogen.
5. **Nitrogen fixation:** the reduction of elemental nitrogen to ammonium and organic nitrogen by free-living micro-organisms and micro-organisms association with nodules in the roots of higher plants.

### Impact of nitrogen mismanagement

Several possible adverse effects from high levels of fixed nitrogen, due to man's activities, have been identified. These include:

1. high nitrate levels in drinking water;
2. eutrophication (nutrient enrichment) of lakes;
3. formation of carcinogenic N-nitroso compounds;
4. acid rainfall; and,
5. destruction of the ozone layer due to excess loss of N<sub>2</sub>O during denitrification.

High nitrate levels in drinking waters are associated with a disease of infants called methemoglobinemia. This occurs only in infants less than three months of age, is readily detected and completely reversible. The general consensus is that it does not pose a large threat to human health.

High nitrate levels (10 mg NO<sub>3</sub>-N/L) have been found in ground waters in New Zealand (Keeney and Gregg, 1982). No attempt has been made to identify the source of this nitrate, although it has been suggested that intensively grazed grass-clover swards were a likely source in the Waikato. Drainage waters from grazed pastures in the Manawatu have contained up to 20 mg NO<sub>3</sub>-N/L, and it was considered that this nitrate came from leaching of urine-affected areas of grazed pastures. Increasing areas of tile-drained and nitrogen-fertilised land, and higher stocking rates on pastures, could increase the problem of high-nitrate ground waters.

Eutrophication of lakes and estuaries is associated with high levels of both nitrogen and phosphorus in the water. Phosphorus is regarded as the limiting nutrient in most freshwater lakes, although there is some evidence that nitrogen is limiting in some. Nitrogen is almost always the limiting element in estuaries. In New Zealand, nitrogen inputs from agriculture may be increasing the productivity of near-shore waters, including the Avon-Heathcote estuary near Christchurch and parts of the west coast of the North Island (Keeney and Gregg, 1982).

### PHOSPHORUS

Australia is unique among the more developed countries in its close dependence on phosphatic fertilisers. These have until quite recently accounted for 85-90% of our total fertiliser use - now about 400,000 t P/yr, mainly as superphosphates. Our use of phosphorus relative to nitrogen and potassium is particularly high compared with Europe and North America. For Australia the ratio N:P:K used is 0.6:1.0:0.25 compared with ratios of 3.5:1.0:1.5 and 3.2:1.0:1.9 for the USA and United Kingdom respectively.

In their natural state, most Australian soils are deficient in phosphorus.

There are some important exceptions, mainly in northern New South Wales and south-eastern Queensland, but unfortunately these are few.

The widespread occurrence of phosphorus deficiency is the result of several unusual features of the geological and pedological histories of the continent. These histories have led to the development of many strongly leached, highly weathered soils of low fertility, together with younger soils which have been developed from parent materials affected by earlier phosphorus-depleting weathering cycles.

Following the commencement of cropping in Australia, cereal yields declined steadily during the latter part of the last century largely as a result of exhaustion of available soil phosphate. From about 1900, cereal yields have increased steadily following the recognition of the need for phosphorus and acceptance of the use of superphosphate. Although other factors, including improved crop varieties, and better rotations and farming practices, have contributed to these increases, the continued use of phosphatic fertiliser has been essential to them.

The use of superphosphate extended to pastures in the 1920's especially in association with the development of subterranean clover as a pasture legume. This was to prove an outstanding step in Australian agriculture because most of our soils, in addition to being deficient in phosphorus were also nitrogen deficient. Initially the introduction of the legume was primarily intended to increase pasture production but it has also provided the remedy for the deficiency of nitrogen both in pastures and in crop rotations. It has also restored and maintained soil organic matter levels and soil structure important to much of our cereal cropping areas. Phosphorus is essential to the growth of the clover so that, apart from their importance in their own right in correcting phosphorus deficiency, phosphate fertilisers have indirectly played an essential role in providing a major part of our nitrogen requirements for agriculture.

Between 1970 and 1980, Australia produced 4 million tonnes of single superphosphate equivalent, 3 million tonnes being applied as single superphosphate. If superphosphate was applied at the rates recommended by extension workers, to the 20 million hectares of cereals and 26

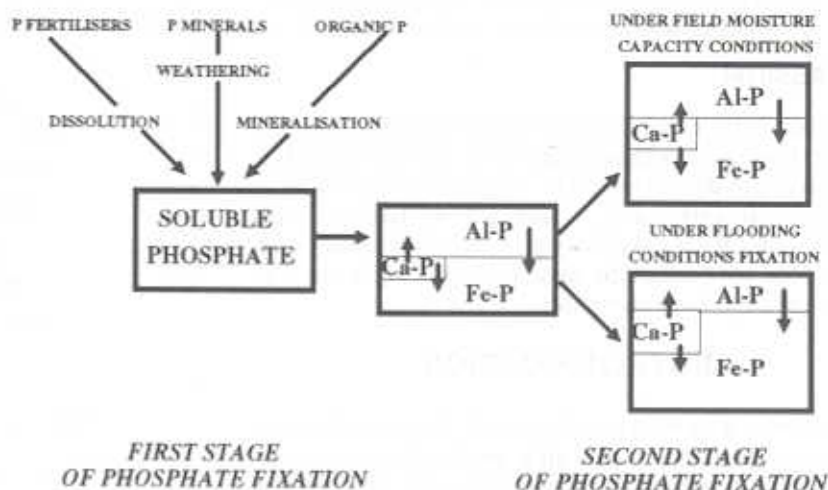


Figure 1: Fixation and transformation of phosphate in soils (Chang and Chu, 1961).



million hectares of fertilised pastures likely to be in production by the end of the decade, 8 million tonnes would be required.

Unlike nitrogen the reactions of fertiliser phosphorus in soils are extremely complex, with scientists still arguing about the fate of applied P. Primarily, the end result is that P forms compounds of extremely low solubility with iron and aluminium. Recovery of P topdressed on a pasture may be as low as 10% in the year of application, with P residues becoming less available with time as illustrated in Figure 1. The boxes in Stage II fixation show the relative proportion of phosphate fixed as Al-P, Fe-P and Ca-P. For example under flooded conditions, more phosphate is fixed as Fe-P than is the case in soil at field capacity (Figure 1).

The clay fraction is the main site of phosphate fixation. In the clay, the content of aluminium is much higher than that of either iron or calcium. Therefore, the added soluble phosphate is most likely to be fixed as aluminium phosphate and not iron phosphate or calcium phosphate in the initial stage of the reaction. As time elapses, the phosphates would change to the less soluble iron phosphate. Since soil is a heterogeneous system and the mobility of the ions in soil moisture is also rather restricted, the rate of change is slow and increases with the moisture content.

The important consequences of these reactions in determining fertiliser requirements and losses of P from the system include:

- P does not move far from where it was placed because of the rapid reaction and insolubility of the new compounds. In all except very sandy soils it only moves 1-5 mm from the fertiliser granule. This means the surface applied phosphate is only available to plant roots at the surface and when soil is moist.
- This lack of mobility also means that water soluble P is seldom leached from soils. Any loss of P is usually in the organic form (manures) or when bound to clay. Loss of either form only occurs when erosion takes place. Even then (since it is not in solution), it does not readily contribute to eutrophication. Only on very sandy soils is water soluble phosphate leached into drainage water. Lewis *et al.* (1981) found that in the south east of South Australia, up to 30% of applied phosphorus was leached from sandy surface soils.

## POTASSIUM

Except in the banana industry where very high rates (600 kg/ha) are applied, potassium applied to pastures should not be a hazard to the environment. It is held by the soil as an exchangeable cation and is taken up by pastures fairly rapidly. Leaching is only likely to occur on very sandy soils, and it does not present the same problems in the environment as nitrogen and phosphorus.

## EUTROPHICATION

Eutrophication refers to the growth of a particular algae in dams and waterways. This algae produces toxins poisonous to both human and animal life. Both nitrogen and phosphorus must be present in the water for it to grow. Either element occurring on its own will not present a problem. Most waters contain some nitrogen compounds

(often organic), and thus it is usually the addition of phosphorus that allows these blooms to occur. The water is often stagnant, *ie.* no flow in rivers or in a dam.

The problem is given great prominence in the media with agriculture being blamed, *eg.* cotton growers polluting the Darling when in fact they use no phosphate. This is not only because agriculture is visible, but powerful lobby groups hide the real culprit which in most cases is sewage effluent discharge.

Many papers (*eg.* Raper, 1983) have demonstrated the dependence of algal growth on phosphorus concentration in the water and that P levels of 0.02 mg/L will not support visible algal concentrations, even in clear water.

Phosphorus may be introduced into streams as run-off from pasture, forests and fertilised land and in drainage from irrigated land and urban areas. These sources, though significant in total, normally contribute low concentrations of phosphorus, and are referred to as non-point sources. Point sources, such as sewage or drainage from dairies and feed lots, contribute smaller flows but contain higher concentrations of phosphorus by several orders of magnitude. Point sources are more amenable to control, and are frequently responsible for the majority of the phosphorus load in a receiving body of water (Loehr, 1974).

Techniques for reducing the level of phosphorus in run-off from agricultural land are based on the fact that the phosphorus is largely in a particulate form or is absorbed on soil or clay particles. Because there is little soluble phosphate present in the run-off, erosion control should suffice to reduce phosphorus to acceptable levels (Loehr, 1974). On the other hand, the phosphorus in point-source effluent is largely in the water soluble form, while in urban or agricultural drainage 50% or more is in insoluble forms. The contribution of phosphorus loads in rainfall, runoff from forests and pasture, and drainage and irrigation return flows has been regarded as small, natural and uncontrollable.

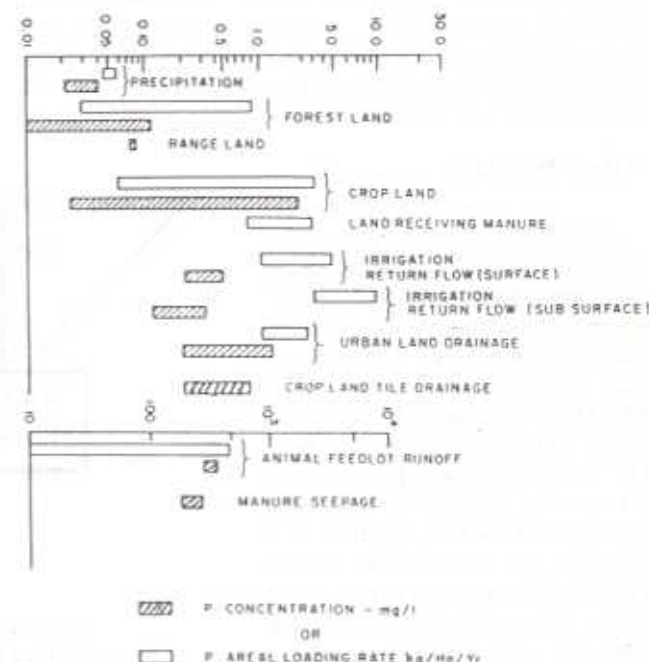


Figure 2: Contribution to eutrophication from various sources (Loehr, 1974).



Recently, the availability of detailed information on the characteristics and magnitude of non-point-source discharges has led to questions about the validity of prior assumptions regarding their likely contributions to eutrophication. Loehr (1974) presented a compilation of data, mainly from USA, which is summarised in the figure below. The sources were compared both in terms of concentration (mg/L) in run-off or drainage and in area yield (kg/ha/yr). Although the range of results is frequently rather wide, data from European areas are essentially similar to those from the Canberra area (Raper, 1983).

## GROUNDWATER POLLUTION

As discussed in the section under nitrogen, leaching of nitrate may present a serious health hazard. It also contributes to soil acidification. When high rates of nitrogen are used or where clover grass pastures fix substantial nitrogen, especially on sandy or permeable soils, inevitably some nitrate is leached which may enter ground-water if there is a water table. When this groundwater is used for domestic supplies, there is the potential for a serious health hazard.

## SOIL ACIDIFICATION - A NATURAL PROCESS OFTEN ACCELERATED IN AGRICULTURAL ECOSYSTEMS

Since soil acidification is soil degradation, any process which contributes to acidification will in the long-run affect the environment.

Legume nitrogen in many cases makes a significant contribution to soil acidification, and since phosphorus fertiliser is required for legume growth, a discussion of soil acidification is appropriate. In addition, the various nitrogen fertilisers available can have different effects on acidification (see Practical Strategies).

### Acid sources

Soil formation usually proceeds from alkaline pH levels (7 to 9) that characterise the weathering surface of most parent rocks, to soil acidity values of pH 3.5 to 4.5 in highly weathered acid soils. In NSW, soils representing this range of pH'S occur naturally. Some of our most acid soils (pH 4.0) are inherently acid and include the earthy sands of the Dubbo-Narrabri (Pilliga) area. They are high in exchangeable Al to depths of a metre or more. These soils have severe production limitations and have been largely left undeveloped for agriculture.

The processes responsible for soil acidification have been comprehensively reviewed by Porter and Helyar (1987). The acids causing the acidification of agricultural soils in NSW are derived mainly from the nitrogen and carbon cycles. Nitric acid is produced during the nitrification of N in proteins, and organic acids are produced in plants from the neutral sugars produced by photosynthesis from CO<sub>2</sub> and water.

### Acidifying processes

The major acidifying processes in NSW agricultural systems are:

- Nitrogen addition through N<sub>2</sub> fixation followed by loss of NO<sub>3</sub> by leaching or run-off.

- Organic acid production from photosynthetically fixed carbon, followed by: (a) the export of residually alkaline organic anions in products, and (b) the accumulation of organic anions as soil organic matter.
- Nitrogen addition as fertiliser in the forms NH<sub>3</sub>, NH<sub>4</sub>OH, urea or NH<sub>4</sub>NO<sub>3</sub> coupled with leaching or runoff losses of NO<sub>3</sub>- (one H<sup>+</sup>/NO<sub>3</sub>- lost).
- Nitrogen addition as fertiliser in the forms (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or NH<sub>4</sub>H<sub>2</sub>PO<sub>4</sub> (monoammonium phosphate) followed by loss as nitrate (two H<sup>+</sup>/NO<sub>3</sub>- lost).

### Acidification rates

Typical acidification rates (expressed as the amounts of lime needed to neutralise the acid added) for some agricultural systems are:

1. 150 to 250 kg CaCO<sub>3</sub>/ha/yr for annual subterranean clover pastures in the 700-900 mm rainfall zone of southern NSW;
2. 100 to 200 kg CaCO<sub>3</sub>/ha/yr for the 500-700 mm rainfall pasture/crop zone of southern NSW and north-east Victoria;
3. 75 to 150 kg CaCO<sub>3</sub>/ha/yr for perennial, grass/clover pastures in the 750-1200 mm rainfall zone of northern NSW; and,
4. lower acidification rates probably characterise the lower rainfall areas, and possibly the higher rainfall strongly perennial environments where soil pH values are already around 5.0 or below.

The main acids that cause soil acidification are carbonic acid formed when carbon dioxide dissolves in water, nitric acid formed when plant proteins or ammonium and urea fertilisers are nitrified in soil, and various organic acids formed by plants and micro-organisms. Some systems acidify slower.

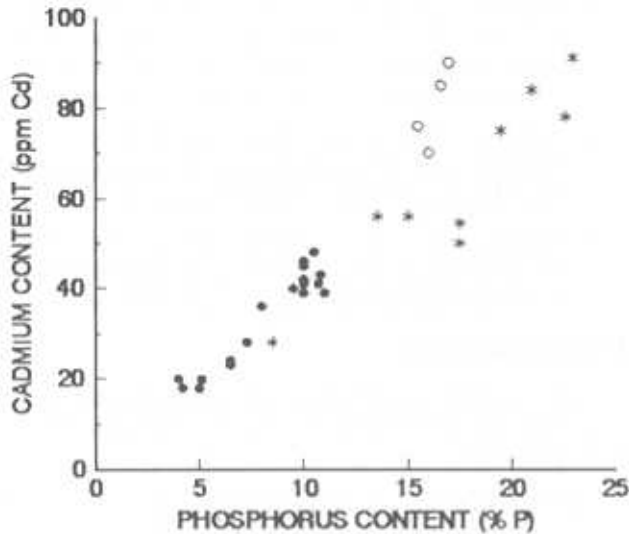
### Management practices to reduce acidification

Management practices that contribute to reduced acidification rates have been reviewed by Cregan and Helyar (1986). The practices are based on developing systems in which nitrogen and water are utilised more efficiently. As well as acidifying more slowly, these are systems in which the two inputs most critical to yields (N and water) are used efficiently.

The main practices that lead to lower acidification rates are:

1. Use less acidifying nitrogen fertilisers after considering the relative costs (see practical strategies).
2. Minimise nitrate leaching by:
  - minimising water percolation below the root zone: use perennial deep-rooted species; minimise periods without active plant growth; and avoid excessive irrigation.
  - minimising nitrate leaching below the root zone: all the above points for water management, plus; incorporate stubbles into fallow to minimise net nitrification; sow early to maximise the opportunity of the crop to recover soil nitrate; use deep rooted crops such as wheat or





- Single superphosphate and mixed fertilisers containing it.
- \* High analysis fertilisers prepared from phosphoric acid.
- Rock phosphates

Figure 3: The relationship between the phosphorus and cadmium contents of some Australian phosphate fertilisers (Williams, 1977)

lucerne in preference to less vigorously rooting crops such as lupins or possibly sunflowers; and use perennial deep rooted species able to maintain low soil nitrate levels in all seasons, or rapidly absorb mineralised nitrate at the break of season.

### 3. Minimise carbon cycle acidification by:

- minimising removal of products high in organic anions. The lime required to balance product removal in kg  $\text{CaCO}_3$ /tonne product, is 55-60 for lucerne and clover hay, 35 for grass hay, 22 for cereal hay, and 3 for cereal grain.
- minimising waste product removal (sheep camp management, dairy night paddock rotation).
- feeding hay on hay cutting paddocks.
- using cropping rotations to minimise excessive accumulations of soil organic matter under pastures.

## CADMIUM

Cadmium is important because it is a cumulative poison and in recent years has come under suspicion as an environmental contaminant that could prove harmful to human health. Levels of cadmium in food crops that might prove harmful are well below those at which plant growth is affected.

Although threshold levels for long-term toxic effects are not known with any certainty, the World Health Organisation has provisionally recommended that intake of cadmium should be limited to 400-500 microgram per week. This value, which undoubtedly contains a substantial safety factor, is not much higher than average dietary intakes in many parts of the world including Australia. As a result, all

sources of entry of cadmium into the food chain have been closely studied.

### Fertiliser cadmium

The cadmium in phosphate fertilisers appears to be derived entirely from the rock phosphate from which they are made. This is indicated in Figure 3 which shows the relationship between cadmium and phosphorus in some Australian fertilisers and rock phosphates used for their manufacture.

### Soil cadmium

The amounts of cadmium naturally present in soil are small. Generally there is less than 0.5 ppm and very commonly, less than 0.1 ppm. Thus although the amounts present in fertilisers are also small - on average about 42 ppm in Australian superphosphate - these amounts are relatively large in terms of the amounts naturally present in soil.

Like any other metal, cadmium is strongly adsorbed by soil and readily accumulates in it so that in the long-term, additions from fertiliser can bring about appreciable changes in the level of soil cadmium. Application of 1000 kg of superphosphate per ha will increase the cadmium content of the surface 10 cm of soil by about 0.03 ppm. In some soils this is sufficient to more than double the original content.

### Plant uptake

The effect of the addition of cadmium to soil on the cadmium content of plants varies greatly and is affected by several factors. Plant uptake is usually small, and the amount of cadmium finding its way into the plant tops rarely exceeds 5 or 6% of that added to the soil. There are, however, considerable differences between plant species.

For example the cadmium content of subterranean clover was 3-5 times higher than that of oats grown under identical conditions. This reflects a greater capacity of the clover to take up cadmium from the soil.

### Distribution of cadmium in plants

As might be expected the cadmium concentration usually varies within the plant itself and this is most important when considering the effects that changes in soil cadmium might have on food crops.

Cadmium was highest in the roots and lowest in the grain of wheat, oats and peas and with these three species less than half of the total cadmium taken up was translocated to the plant tops and less than 5% found its way into the grain. With tobacco, however, most of the cadmium was translocated to the tops and most of it accumulated in the leaves.

### Effect of soil on cadmium uptake

The soil also plays a major part in determining cadmium uptake. The effect of soil is indicated in the next table which shows the uptake of cadmium by oats from three different soils in pot culture. These soils all had similar pH (about 6.0) but differed in clay content, organic matter content and other properties. Addition of 0.2 ppm cadmium to soil 1 increased the cadmium content of the oats to 0.44 ppm, where on soil 3 the increase was only to 0.13 ppm. The recovery of added cadmium by the oats ranged from 0.5% from soil 3 to 2.2%

from soil 1.

### Practical significance of cadmium in superphosphate

It is clear that many interacting factors determine the effects that the cadmium impurities in fertilisers might have on the cadmium content of plants. However, while information is still somewhat limited, it seems reasonable at this stage to attempt some assessment of their likely importance.

As far as the plant is concerned, its effect will be least on alkaline soils and on heavy textured soils with a pH of 6 or more, and greatest on acid, light textured soils.

In many cases its effect will be small because of the crop species involved and the portion of the plant harvested. Cereal crops, for example, have a low capacity to take up cadmium and only transfer a small part of it to the grain. Cadmium is also of no importance in sugar and fibre crops.

Cadmium impurities also seem to be of little consequence as far as pastures and fodder crops are concerned. There has been no evidence that fertiliser cadmium has any adverse effect on animal health and, except for the kidneys, its effect on the cadmium content of meat or milk seem to be very small.

Although it appears that cadmium has little importance in limiting plant and animal production, there is a worrying factor affecting human health. Cadmium in plants eaten by grazing animals accumulates in offal and may reach very high concentrations. The problem is particularly bad in areas of South Australia and Western Australia where there are large areas of sandy soils. Offal in these areas has levels of cadmium sufficiently high to prevent export of these animal parts. On other soils, with even a low clay content, this is not believed to be a problem.

## SOCIAL IMPLICATIONS

The adverse publicity given to the role of agriculture in polluting the environment by the media produces a feeling of guilt in the farming community and can lead to reductions of fertiliser input which then result in production losses. The consequences of this are far reaching. If production

capacity per unit area is significantly reduced then the cost of product may rise to a point where sales of end product are affected. Incomes of producers may be seriously affected.

It is important for the rural community to be aware of the effects of fertiliser and the need to use them carefully. It is also equally important that the scientific community set the record straight in the public media as to the sources of pollution.

A further factor to be considered is the impact of reduced fertiliser use on plant cover or pasture density. If reduced fertiliser inputs result in increased areas of bare soil, then erosion risks are substantially increased. The impact of this on sustainability, eutrophication and water quality may be substantial. Other factors to consider may be weed invasion, increased vegetable matter in wool and reduced conception rates.

## PRACTICAL STRATEGIES

Where aerial or ground topdressing of superphosphate is used then some of the more obvious things not to do are:

- Do not topdress dams, streams or swampy areas
- Do not topdress bare ground
- Maintain good ground cover around dams and streams
- Try to avoid that time of the year when heavy cyclonic rain is expected.
- With nitrogen fertilisers, the first option is better management. Total fertiliser should be split into several smaller applications to minimise leaching. The second is to change the form of nitrogen to reduce acidification. Table 1 shows the lime equivalent (in kg) for each kg of nitrogen applied for two situations:

1. where all applied N is taken up;
2. where all applied N is leached; and
3. Clearly there are large differences.

Helyar (1991) has discussed the use of perennial pastures in reducing acidification from nitrogen as well as the management options.

**Table 1: Acidification potential of a range of fertilisers (Helyar, 1991)**

Fertiliser & acidification class	CaCO <sub>3</sub> (lime) to balance acidification where leaching is:	
	Nil	100% of N applied (kg lime/kg N)
<b>(A) Not acidifying - ammonium fertilisers:</b>		
Sulphate of ammonia (ammonium sulphate)	3.7	7.1
MAP (monoammonium phosphate)		
<b>(B) Medium acidification:</b>		
DAP (diammonium phosphate)	1.8	5.3
<b>(C) Low acidification:</b>		
Urea		
Ammonium nitrate		
Aqua ammonia		
Anhydrous ammonia	0	3.6
Biologically fixed (legume) N		
<b>(D) Alkaline fertilisers</b>		
Sodium and calcium nitrate	-3.6	0

## REFERENCES

- Chang, S.C. and Chu, W.K. (1961). The fate of soluble phosphate applied to soils. *Journal of Soil Science*, 12: 286-293.
- Cregan, P.D. and K.R. Helyar (1986). Non-acidifying farming systems. In "Acid soils revisited", *Proceedings of the 15th Riverina Outlook Conference, Riverina-Murray Institute of Higher Education, Wagga Wagga*, pp. 49-62.
- Helyar, K.R. (1991). Do perennial pastures reduce soil acidity? *Proceedings of the Sixth Annual Conference of the Grasslands Society of NSW*, pp. 64-71.
- Kecney, D.R. and P.E.G. Gregg (1982). Nitrogen fertilisers and the nitrogen cycle. In (Ed.



- Lynch, P.B.) *New Zealand Institute of Agricultural Science*.
- Lewis, D.C., A.L. Clarke and W.B. Hall (1981). Factors affecting the retention of phosphorus applied as superphosphate to sandy soils in south eastern South Australia. *Australian Journal of Soil Research*, **19**: 167-74.
- Loehr, R.C. (1974). Characteristics and magnitude of non-point sources. *Journal of Water Pollution Control Federation*, **46**: 1849-72.
- Porter, W.M. and K.R. Helyar (1987). Soil acidification, its measurement and the processes involved. In "Soil acidity and Plant Growth", Edited by A.D. Robson, J.S. Yeates and W.M. Porter. *Adademic Press*, (in press).
- Raper, W.G.C. (1983). Water pollution - Sewage recycling. In "Phosphorus in Australia" Edited by A.B. Costin and C.H. Williams. *Australian National University*, Canberra.
- Williams, C.H. (1977). Trace metals and superphosphate toxicity problems. *The Journal of Australian Institute of Agricultural Science*, **43**: 99-109.