# Soil chemistry – facts and fiction and their influence on the fertiliser decision making process

N. Menzies,[A] D. Harbison [B] and P. Dart[A]

[A]The University of Queensland. [B]D R Agriculture Pty Ltd.

*Take home message: Trust nobody! – test it yourself, but test it properly.*

## Preamble – the legal problem presented by speaking about products

One of the first constraints to a scientist in presenting a paper like this, is the risk that the statements made, may be viewed by those with a commercial interest in selling products to farmers, as so damaging (or so wrong) that they need to respond by taking legal action against the scientist. Even the threat of legal action may be so daunting that the scientist or the employer may prefer to remain silent. One of the most celebrated examples of this is the Maxicrop case, in which the Bell-Booth Group sued the New Zealand Ministry of Agriculture and Fisheries (MAF) and Dr Doug Edmeades personally for damages (initially $5.5 million, later amended to $11.5 million). This story is wonderfully presented in Edmeades' book 'Science Friction. The Maxicrop case and the aftermath' (Edmeades DC 2000. ISBN 0 473 06886 9, Published by Fertiliser Information Services Ltd., P.O. Box 9147, Hamilton, New Zealand), and the underlying science published in the Australian Journal of Agricultural Research – Edmeades DC 2002. The effects of liquid fertilisers derived from natural products on crop, pasture, and animal production: a review. *Australian Journal of Agricultural Research* **53**, 965–976. A snap shot of the case is reported here, as it provides some insight into how some 'responses' can be obtained.

Maxicrop is a concentrated seaweed extract, which was promoted as a fertiliser, providing nutrients and plant hormones. The recommended application rates, highly diluted, meant that it was considerably cheaper than conventional fertilisers. As with farmers everywhere, New Zealand farmers in the mid-1980s were subject to economic pressures, and with fertilisers as a major cost a cheaper alternative was welcomed. After extensively reviewing the world literature on non-traditional fertilisers, analysing Maxicrop, and undertaking field trials with it, Dr. Edmeades came to the conclusion that, used as directed, the product could not possibly provide the claimed benefits. In April 1985, Dr. Edmeades appeared on the TVNZ program 'Fair Go' with Mark Bell-Booth and David Bellamy in which he presented his case against Maxicrop. It was this program which provided the basis for the subsequent legal action.

One aspect of the company's case was the claim that Maxicrop did work in some situations (increasing crop yield), and while they could not accurately predict which conditions it would work under, there was nevertheless evidence that the product did work. The real difficulty for Doug Edmeades and MAF was to explain to people trained in law, rather than natural sciences, that natural variability (in statistical terms – error) would result in Maxicrop occasionally producing a yield greater than the control. One of the key pieces of information that helped the lawyers grasp this idea was a set of data showing the response of crops to an application of water (Figure 1, from Edmeades 2002).

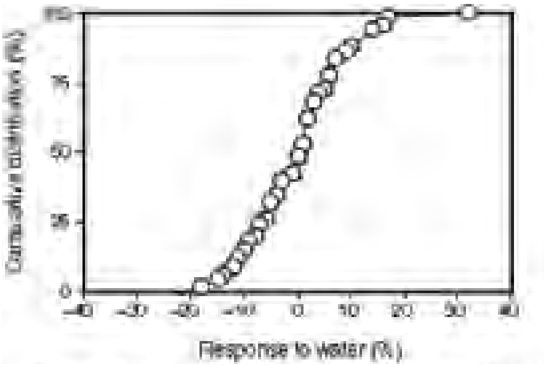

**Figure 1. Frequency distribution of crop responses to water (225 L/Ha) expressed as the increase or decrease (%) relative to the control (data from Wadsworth 1987).**

From Figure 1, you can see that occasionally an application of water reduced crop growth (by almost 20% in a very small number of instances). Conversely, water also increased yield in some instances. The key aspect of this set of data is that the data points are centred around zero (the mean is actually –0.6% and confidence interval 2.3%). In fact, the application of water had no effect on yield, the range of results obtained is consistent with variability normally associated with this type of experiment.

Using this basic understanding of variability, it was apparent to the court that Maxicrop did not work, and that the occasions when it appeared to increase yield were simply random variation (experimental error). Frequency distributions for Maxicrop and several other similar liquid fertilisers are presented below overlaid with the response to water in each of the trials (Figure 2 from Edmeades 2002). Overall a great demonstration that materials of this type (low nutrient concentration, and compounds intended to act as plant growth stimulants) are not effective fertilisers.

Ultimately, the judgement mostly went against the plaintiffs except in one regard. In relation to the claim of negligence the judge, Justice Ellis, stated, 'MAF is in the most general way under a duty to act fairly to all citizens. This involves balancing competing interests. The present case is a good example. MAF must in my view balance its primary obligations and duties to the pastoral and agricultural industries and to the vendors of products consumed by such. In general terms, I consider that where an agency such as MAF intends to condemn a product it must give the seller an adequate and fair opportunity to consider such publicity beforehand and make its responses before the damage is done.' Consequently his Honour found that MAF had breached this duty of care and had acted negligently, awarding the Bell-Booth Group $25,000.

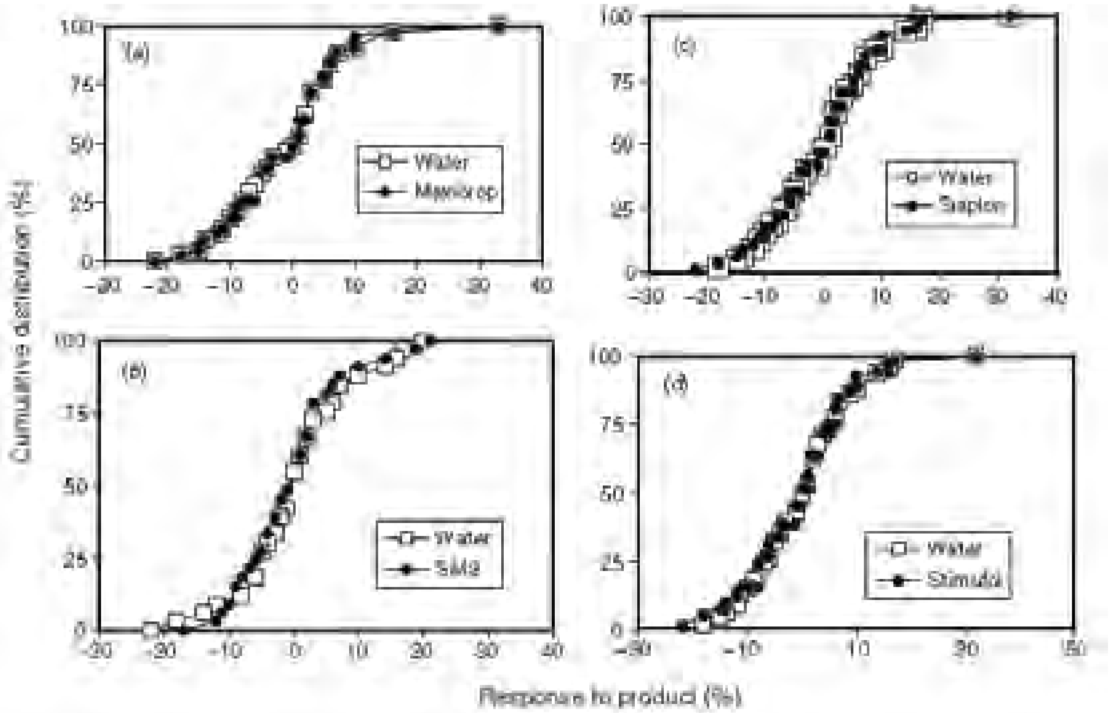

**Figure 2. Frequency distributions for Maxicrop (seaweed), Siapton (animal offal extract), SM3 (seaweed), and Stimufol (vegetable).**

The company was not satisfied with this tiny victory and appealed to the Court of Appeal, which provided no encouragement and overturned the negligence verdict, observing *inter alia* that, 'Some of the arguments for the company go close to asserting that a manufacturer has a right to sell worthless goods as long as he honestly believes that they are some use. We would see that as putting it over-simply. Those who reasonably believe that the goods are worthless must have an equal right to say so.' Despite the clear defeat of the plaintiff, who had initiated the case, the view was widely expressed that the powers of government had been used to crush a small struggling entrepreneur.

Despite the eventual court decision, the case cost Doug Edmeades at least 18 months of his professional career; it was undoubtedly also a most harrowing experience. Further, as explained by Dr Edmeades in 'Science Friction' MAF were subsequently very hesitant to allow their scientists to publish results that did not support a commercial product. 'How does this help farmers?' we might well ask. We have no desire to follow in Doug's footsteps, so we are setting some rigorous rules in what we intend to say and how we can justify these statements. Throughout this paper, we will stick to reporting to you the 'science' (Doug Edmeades also did this, but it still was not enough to keep him safe). We will not refer to specific products. However, we do want to provide you with something useful, so we will attempt to provide you with a way to think about products which are intended to improve plant growth through their influence on soil biology. We also make some suggestions of how to go about testing these products yourself.

## The nature of science and of faith – we will stick to science

The basic nature of science is to form a hypothesis which explains an observation; this hypothesis is then tested. If through repeated testing the hypothesis is shown to account for the observations, then it is regarded as a theory. In scientific terms, 'theory' does not mean 'guess' or 'hunch' as it does in everyday usage. Scientific theories are explanations of natural phenomena built up logically from testable observations and hypotheses. Scientists generally use the term 'fact' to mean something that has been tested or observed so many times that there is no longer a compelling reason to keep testing or looking for examples.

In contrast, faith is something one 'believes in'. It serves a major evolutionary purpose and has been an essential part of human nature since time immemorial. When shared by members of a group, faith strongly supports that group's internal cohesion. It strengthens the group's capacity to cope with the challenges of a hostile environment. It adds to the group's capacity to compete successfully with other groups animated by different faiths. But there is a dark side to the 'in group' – whether religious or not – by definition, there is an 'out-group'. A basis for hostility – often extreme – if we are not careful. All religion is based on faith, but not all faith needs to be religious, at least in the sense of requiring adherence to a recognised religious persuasion (from Carl Croon – Progressive Humanism).

## Clarity at the extremes

Let's briefly look at examples that are readily accepted as sitting near the opposing ends of this Science – Faith spectrum.

## One clear endpoint – Science; illustrated by symbiotic $N_2$-fixation

The rhizobium–legume symbiosis is a good example of science. In this unique association between organisms, the plant provides a source of energy and an ecological niche for the bacterium, which in return synthesises ammonia for the host plant. Despite millions of years of evolution, higher plants have not developed a $N_2$-fixation system. At the global scale, the rhizobium-legume symbiosis provides a quantity of fixed nitrogen (N) comparable to that produced by the entire chemical fertiliser industry, and thus plays a major ecological and economic role (Table 1). The symbiosis has been the subject of a great deal of scientific investigation, and we now understand it at a genetic, biochemical and ecological level. Furthermore, we understand it well enough that the system can be, and is, effectively manipulated in farmers' fields all over the world.

**Table 1. Major annual terrestrial N inputs. Fixation by legume crops is subdivided to show the importance of soybean. (Simil 1997; Herridge *et al.* 2008).**

| Source | Nitrogen fixed (Tg) | |
|---|---|---|
| Natural biological N fixation | | 90–140 |
| Lightning | | <10 |
| Symbiotic N fixation by crop legumes | | 22 |
| Soybean | 16 | |
| Peanut | 2 | |
| chickpea | 0.6 | |
| Pasture legumes | | 12–25 |
| Fertiliser | | 160 |

This is a true symbiosis – each organism gains an advantage – the rhizobium with energy and the legume with fixed N.

## The other clear endpoint – faith; illustrated by homeopathy

At the other extreme, homeopathy is viewed by scientists as representing an example of faith. A central thesis of homeopathy is that an ill person can be treated using a substance that can produce, in a healthy person, symptoms similar to those of the illness. Practitioners select treatments based on consultation that explores the physical and psychological state of the patient (not a bad idea!), both of which are considered important to selecting the remedy. According to Hahnemann, one of the key figures in the development of the approach, serial dilution, with shaking between each dilution, removes the toxic effects of the substance, while the essential qualities are retained by the diluent (water, sugar, or alcohol). Claims to the efficacy of homeopathic treatment beyond the placebo effect are unsupported by the collective weight of scientific and clinical evidence. Common homeopathic preparations are often indistinguishable from the pure diluent because the purported medicinal compound is diluted beyond the point where there is any likelihood that molecules from the original solution are present in the final product; the claim that these treatments still have any pharmacological effect is thus scientifically implausible and violates fundamental principles of science. Critics also object that the number of high-quality studies that support homeopathy is small, the conclusions are not definitive, and duplication of the results, a key test of scientific validity, has proven problematic at best. The lack of convincing scientific evidence supporting its efficacy and its use of remedies without active ingredients have caused homeopathy to be regarded as pseudoscience or quackery (from the reference most loved by university lecturers – Wikipedia). Also, in some instances, a belief in the benefit of a treatment is considered a prerequisite for its efficacy – this precludes scientific testing.

The dilutions advocated in homeopathy are extreme. A $10^{60}$ dilution was advocated by Hahnemann for most purposes. Some trivial calculations put this dilution in context – if you used a medicine diluted to $10^{60}$, you would need to give two billion doses per second, to six billion people (the world's population), for 4 billion years, to deliver a single molecule of the original material to any patient. One third of a drop of some original substance diluted into all the water on earth would produce a remedy with a concentration of about $10^{26}$ (once again I am trusting Wikipedia for this value).

## The difficult middle ground

The extremes are easy – we can readily accept or reject ideas (or products) for which there is clear evidence and understanding on which to base our decision. Our decision-making task is much more difficult when there has been only limited investigation, and hence there is little information, or when the results of investigations appear to be inconsistent.

We will develop two examples here. The first, 'P-solubilisation by freeliving organisms' provides an example where there is a clear underpinning mechanism. The question we will attempt to address is: Can this process be manipulated and enhanced? From the perspective of a farmer, the question would be: Are products which claim to do this, worth the investment? The second example of the 'Ideal Cation Ratio' demonstrates poor science – selecting only the results which suit your viewpoint, even if the research was poorly conducted.

It is very difficult to compare growth of plants with and without microbes, as plants growing with microbes, is the natural condition. Plant roots are surrounded by a mucilaginous layer, the 'mucigel' mainly exuded from the root tip. The space immediately surrounding the root, where microbes grow in greater numbers than in the bulk soil, is known as the rhizosphere which usually extends about 1–2 mm from the root. The plant exudate contains a wide range of amino acids, sugars, organic acids and vitamins. Some bacteria are selectively stimulated to multiply by this substrate. The amount of carbon in the photosynthate exuded into the rhizosphere can be as much as 25–30% of the total amount fixed by photosynthesis.

So much of the plants energy is invested in rhizosphere functions. One of these is to develop a population of microbes, both bacteria and fungi, which protects the plant from infection by pathogens and plays a role in plant nutrition and plant growth stimulation through production of plant hormones. There is a homeostatic process operating in the rhizosphere so that the numbers of a particular organism reach an equilibrium level. The microbes respond to plant signals which affect their gene expression, and also through a process known as quorum sensing, where microbes limit their own population development once a certain level has been reached. Most of the organisms living in the rhizosphere and the bulk soil cannot at present be grown in culture medium. The genetic diversity of the soil microbial population can be affected by the farming system, soil type and plants grown. So we have a very complex system which, as we shall show with our P uptake example, has feedback interactions also. There is a lot we do not know about the plant microbe interactions in the soil. So the way to see if we can manipulate the system to be economically beneficial for sustainable agricultural production is to undertake very well designed empirical experiments properly replicated over time and environment, soil type and farming system.

In the bulk soil and rhizosphere, microbes are responsible for mineralising (breaking down) organic matter, thereby releasing nutrients for plant uptake and growth. The benefits accruing for plant growth from richly organic soils is directly the result of microbial activity. However, all of these benefits are from microbes existing naturally at sufficient populations in soils to undertake this process of mineralisation, growth stimulation, pathogen control, etc. For processes like mineralisation, there is invariably no need to add any more micro-organisms to the soil. In the following sections we explore the question, of whether adding additional organisms is ever effective. We develop this question in our example of plant microbe interactions – it's for you to judge if we have managed to answer it.

## Ambiguity – phosphorus solubilising organisms

After N, phosphorus (P) is the most commonly limiting nutrient in soils around the world. Soils typically have a reasonably large store of P, many soils contain a total P store sufficient for 100 years of farming, but the problem is that most of this P is not in a form which is available for plant uptake. Plants take up P directly from soil solution as orthophosphate ($HPO_4^{2-}$ and $H_2PO_4^-$). As the soil solution P is depleted, other pools of P that are held on the solid phase of the soil will be released into solution. For example, P that is adsorbed to soil minerals desorbs, thus buffering the P in the soil solution. Another pool of P in the soil is organic-P which, like N in the organic matter, needs to be mineralised in order to be available for plant uptake. Typically, 20 to 70% of the total soil P is in this organic pool in mineral soils (values for organic soils and peats are much higher, of course). Many plants, including wheat, can achieve the release of part of this organic-P through the release and action of the enzymes called phosphatases. Production of phosphatase is enhanced by low P conditions. The phosphatase enzymes achieve release of orthophosphate from the soil compounds however, they account for only a minor part of the soil organic-P and generally are not present in soil in sufficient quantities to supply an actively growing plant's needs. Most of the remaining organic-P cannot be readily accessed by the roots of most plants, but release by the plant of root exudates acts as an energy source for organisms which are able to produce enzymes capable of releasing this organic-P. The concentration of organic-P near the roots of wheat can decrease dramatically (by 86% in a study by Tarafdar and Jungk 1987). So organisms which mobilise organic-P are clearly important. In this paper, we will concentrate on organisms which are capable of mobilising P from inorganic forms.

**Plant P solubilisation.** Some plants can themselves solubilise inorganic-P from the soil solid phase in order to make it available for uptake. A few plants that are adapted to low P soils, for example lupin (*Lupinus albus*) excrete acidifying compounds (e.g. citric and malic acids) enabling solubilisation and uptake of P into the plant. Most plants (including wheat and maize) do not appear to do this. Acidification can solubilise P in alkaline soils, but this strategy is not effective in acid soils. Members of the plant family *Proteaceae* are particularly effective at producing and excreting organic acids into the root zone. Plants of this family (and a number of other families) are able to form cluster roots. This structure permits the effect of organic acid release to be concentrated in a limited volume of soil to maximise its effectiveness. We can regard these plants as mining P, by forcing its release from the solid phase. In contrast, the mycorrhizal associations of many crop plants could be considered as scavengers, picking up whatever free P (P in the soil solution) they can find. Mycorrhizal associations are more effective in soils where the soil solution P concentration is somewhat higher than that in soils where *Proteaceae* are abundant (Lambers *et al.* 2008).

It's worth considering the energy (carbon) cost to the plant of obtaining P by different strategies. In soils with a reasonable P status, the roots and root hairs are sufficient to obtain sufficient P. As P becomes more limiting, the plant will invest more of the carbon it fixes through photosynthesis, and this can be seen in an increased root to shoot ratio (more roots and fewer shoots). In still lower P environments, mycorrhizal associations are beneficial to the plant – it costs less energy to support a network of fungal hyphae than it does to build a system of roots and root hairs. For mycorrhizal plants, 4 to 20% of carbon fixed in photosynthesis is used by the mycorrhiza. It is interesting to note that the formation of the plant-mycorrhizal symbiosis is affected by P supply; plants do not form an association in high P soils, as feeding the fungus would represent an unnecessary expenditure in this situation. Finally, the production of cluster roots and release of organic acids is extremely energy expensive; the plants strategy is to acquire P at any cost (Lynch and Ho 2005). It is no surprise that plants which do this are slow growing. Energy cost is clearly critical when we are considering a crop or pasture situation, as any additional investment in obtaining nutrients can reduce yield.

**Free living solubilisers.** Micro-organisms capable of solubilising P are ubiquitous in soils, with 1 to 50% of the total bacterial population, and 0.1 to 0.5% of the total fungal population capable of solubilising P. The P-solubilising bacteria typically outnumber P-solubilising fungi by 2- to 150-fold, though fungal isolates exhibit greater solubilising ability (Gyansehwar *et al.* 2002). The simplest mechanism of P solubilisation by the microbes is through acidification of the organism's growth environment. This acidification can simply be a reflection of the nature of the N supply; organisms supplied with N in the growth medium primarily in the ammonium ($NH_4^+$) form excrete protons in order to maintain electron neutrality (they have the problem of taking up too many cations – $Ca^{2+}$, $Mg^{2+}$, $K^+$, $NH_4^+$, and too few anions – $SO_4^{2-}$, $PO_4^{3-}$, $NO_3^-$, and must balance this by pumping out $H^+$). In poorly designed laboratory experiments, if N is supplied as ammonium, this results in many organisms being able to solubilise calcium phosphate by this mechanism. This is unlikely to happen in soil because nitrate and not ammonium is the normal source of N for the microbes. The other main P solubilisation strategy is the production and release of organic acids, similar to the process described above for plants.

Before leaving the rhizosphere its worth considering how long the organic acids will continue to work for, and how large a zone of influence there may be around a P solubilising organism. Organic acids represent an energy source for soil organisms (food for bugs). Studies on the breakdown of organic acids such as citrate and malate added to soil at realistic concentrations similar to rhizosphere concentrations show that the acids are rapidly degraded in bulk (non-rhizosphere) soil – the half life is about 2 to 3 hours (i.e. microorganisms will degrade half of the organic acid added at these rhizosphere level concentrations to simpler carbon compounds in 2 to 3 hours). In the rhizosphere itself, where there is a much higher population of organisms, degradation will be 2 to 3 times faster (Jones 1998). As for the zone of influence – because organic acids are strongly bound by the soil, they do not move far; the predicted zone of influence for a root is 0.2 to 1.0 mm (Jones 1998). The influence of an individual organism/colony would be a small fraction of this. If we also consider that P is relatively immobile in the soil – clearly, the organism would have to be in the rhizosphere to have any impact on plant growth. Inoculation of the seed, and hence the rhizosphere may work, but treating the bulk soil is very unlikely to be effective.

**Field effectiveness of P solubilising organisms.** The involvement of micro-organisms in solubilisation of P has been known for more than 100 years, and there is a substantial literature dealing with this issue. However, most research has been at the laboratory culture (petri dish), or glasshouse pot trial scale; the number of field trials is quite small. Unfortunately, there is no simple message from the field trials; some trials showed growth enhancement and/or increased P uptake, but there is large variation in the effectiveness of inoculation with P solubilising organisms (Kucey *et al.* 1989; Gyaneshwar *et al.* 2002). Tandon (1987) undertook a review of this research, and while this report is now 20 years old, the conclusions he reached at that time are still applicable today. Tandon reported that inoculation resulted in 10 to 15% yield increases in 10 out of the 37 experiments he considered; in the remaining trials (70% of cases) there was no increase. Furthermore, he (and subsequent reviewers) considered that even in the trials that showed a yield increase, there was reason to question the validity of the findings. Two of his most important concerns were that:

- In many trials, the inoculation with P-solubilising organisms was not compared to addition of soluble P fertiliser, so there is no direct evidence that plants would respond to increased P availability in these soils. (This is still a valid criticism of recent publications – indeed, some papers provide data to show that the plants do not respond to P fertiliser; i.e. that the soil is not P deficient.)
- The mechanism for plant growth promoting activity of P-solubilising organisms, other than P solubilisation, has not been demonstrated, but has often been claimed. For example, claims that the organisms may produce plant hormones which increase growth. Certainly some P-solubilising organisms do produce plant hormones (e.g. indole-acetic acid), but the impact of this on plant growth has not been established.

We undertook a rapid review of papers published since Tandon's 1987 review. On the basis of the number of published papers, research on P-solubilising organisms is concentrated in a limited number of counties (Table 2), with India dominating. Of the field studies published, 10 papers show a yield or biomass increase as a result of inoculation, and seven show no effect. Of the papers showing a beneficial effect of inoculation with P-solubilising organisms, the benefit ranged from a modest increase (e.g. 10%), to more than two-fold increase in one instance. We considered that the results of a further 18 papers could not be reliably interpreted. These papers had one (or several) of three types of limitations.

- The effect of P-solubilising organisms could not be separated from the effect of other beneficial organisms. In several studies, using legume test species, a mixed inoculum consisting of rhizobium, P-solubilising organisms, and other organisms considered to be beneficial was applied. A beneficial effect of N supply through nodulation could be expected.

- In many studies no effort was made to establish that the soil was P responsive at all, or within the range of P application used as treatments. In India, it is common to compare a 'recommended' rate of P fertiliser with a fraction of this rate (e.g. 75%) plus P-solubilising organism inoculation. If these treatments achieve the same yield, the researchers interpret this as a demonstration that P-solubilisation has replaced the remaining (25%) fertiliser. This would only be valid if increasing the fertiliser rate did increase yield, and this was not demonstrated. It may be that 75% of the fertiliser was sufficient to achieve maximum yield, and that the inoculation did nothing.
- A limited number of experiments used treatments of fertiliser, and the same rate of fertiliser plus P-solubilising organism inoculation. If these treatments achieved the same yield, then the researchers interpreted this as a demonstration that P-solubilisation did not occur. Once again, this would only be true if the addition of more P increased plant yield, and this was not demonstrated. It is possible that solubilisation did occur, but the plant was already adequately supplied with P and hence did not grow any better or was limited in its growth by the lack of other nutrients.

**Table 2. Origin and nature of research on P-solubilising organisms.**

| Country where research was undertaken | Total number of papers | Number of field studies |
|---|---|---|
| India | 34 | 16 |
| China | 11 | 4 |
| Brazil | 9 | 1 |
| Turkey | 9 | 5 |
| Canada | 8 | 2 |
| Czechoslovakia | 7 | 2 |
| Others | 19 | 5 |

Organisms which are capable of P solubilisation in the laboratory, often fail to achieve this in soil. This can in part be attributed to the more strongly buffered nature of soil systems (relative to laboratory microbial growth media).

Organisms which produce acid can solubilise P in poorly buffered media, because the pH is easily lowered by production of $H^+$. However, it requires a great deal more acid production to solubilise P in a buffered soil, and few organisms can achieve this. This is especially true for vertosols, which may contain high levels of lime (calcium carbonate), and are thus able to maintain a constant pH even when relatively large amounts of $H^+$ are added.

We have had the opportunity to test P-solubilising bacteria as part of an ACIAR project we have been undertaking in Madhya Pradesh, India, with scientists from the Indian Institute of Soil Science (IISS). The inoculum used was a mixture of P-solubilising bacteria selected to be effective across a wide range of soil types and crops. This inoculum was developed by scientists at IISS, and is available commercially to farmers in India. Four replicated experiments were undertaken (two experiments in two districts) for two years (2005–2006). Individual plots were 60 m x 4.5 m. The five treatments applied were inorganic fertiliser at the recommended rate (100%), fertiliser at 75% of the recommended rate (75%), fertiliser at 75% of the recommended rate plus P-solubilising bacteria (75%+PSB), an organic treatment of 8 t/ha of farm yard manure (Org), and this organic treatment plus P-solubilising bacteria (Org+PSB). The recommended P fertiliser rate for the area is 26 kg P/ha, and this

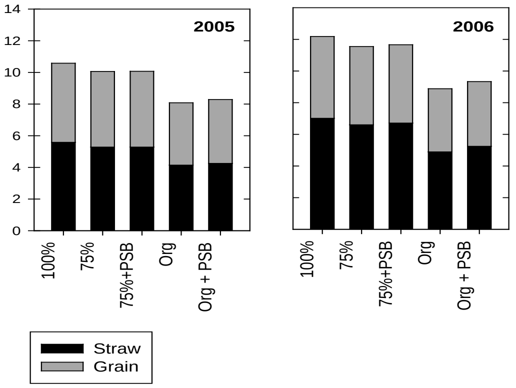

**Figure 3. Average grain and straw yields for wheat grown using inorganic fertilisation, or organic fertilisation, with (+PSB) or without inoculation of seed with P-solubilising bacteria. Yields are the mean of four experiments. The shading of the histogram indicates straw (black) and grain (grey).**

was the rate used in the 100% treatment. Other nutrients likely to be limiting plant growth were identified in earlier glasshouse nutrient omission experiments where growth is compared with a complete nutrient addition and this minus the element under test). These nutrients (in this case N, S, and Zn) were added as a basal application to the 100%, 75% and 75%+PSB treatments. The test crop was wheat, grown in the winter or rabi season and the soil at each site was a vertosol. The crops typically received four irrigations. Across all four experiments in each of the two years, there was no significant grain or straw yield increase (Figure 3), or additional P uptake, as a result of the P-solubilising bacteria.

One final published study, that of Karamanos *et al.* (2010) is worth mentioning, because it considers the organism *Penicillium bilaii*. You will find this is the active ingredient in several commercial products currently available in the Australian marketplace. Karamanos and his co-authors considered the results of 47 experiments carried out from 1989 to 1995 to assess the benefit of *P. bilaii* inoculation of wheat on the Canadian prairie. In 33 of these experiments, there was a response to P fertiliser (i.e. the soil was P deficient). In 14 experiments, there was a response to *P. bilaii* – in five, the inoculation increased yield, and in nine the inoculation deceased yield. These responses appear to be random events. The inoculation with this commercially available organism did not work. Phosphorus fertiliser did work, and would clearly have been a better investment for the farmers. It is important to note that in 14 trials, there was no response to P fertiliser; the soil simply was not P deficient. This highlights the value of soil testing. The soil test response is shown in Figure 4, which shows clearly the yield response to P availability. It also shows clearly the total lack of response to *P. bilaii*.

Where does all of this leave us? We need to consider what benefit could be expected from seed inoculation. As soils contain large numbers of organisms capable of solubilising P, inoculation would only be of benefit if the inoculated strain was much more effective than the organisms already present in the soil. On the basis of the published literature, inoculation does appear to work sometimes (*albeit* infrequently), but the circumstances in which this will occur reliably have certainly not been established. At this time we are unable to predict when a positive response will be obtained. A series of trials over different years, in a range of soil types would be needed to establish the reproducibility of the response. Rarely is this done with microbial inoculation experiments, and the example we considered (Karamanos *et al.* 2010), provides a clear demonstration that for the organism tested there was no benefit. When inoculation with P-solubilising organisms does work, most trials have shown a modest increase in P availability and of crop yield (somewhere in the 10% range). When you consider the substantial energy cost of P solubilisation, a modest increase is probably all you should expect.

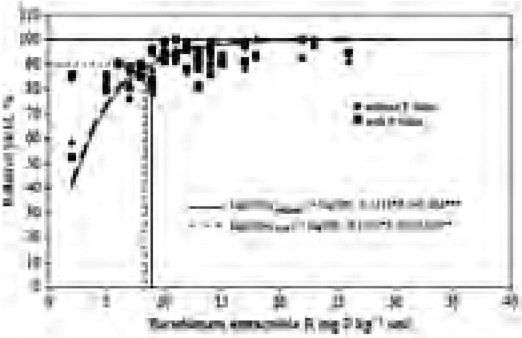

**Figure 4. Soil test calibration curve for bicarbonate extractable P with wheat ( + or – *P. bilaii*). Relative yields are a percentage of the yield obtained with a P application of 13.1 kg/ha.**

## Poor science – the ideal cation saturation ratio

Our early understanding of crop nutritional requirements and their response to soil conditions came through observation; the progressive development of hypotheses about soil-plant relationships which could then be rigorously tested. The concept of ideal cation saturation ratios has this history. During the 1940s and 1950s there were a series of reports proposing 'ideal' proportions of exchangeable cations in soil (Bear *et al.* 1945; Bear and Toth 1948; Graham 1959). The proposed ranges were 65 to 75% $Ca^{2+}$, about 10% $Mg^{2+}$, 2.5 to 5% $K^+$, and 10 to 20% $H^+$, or approximate ratios of 7:1

for Ca/Mg, 15:1 for Ca/K, and 3:1 for Mg/K. Without question, soils with this cation make-up would not present any problems for plant growth with respect to these nutrients. However, our question is, 'will plants grow better if we adjust the cation ratios of the soil to these values?' A couple of key points need to be made about this approach:

- The method was proposed by scientists working in areas of the USA where there are very good soils with negligible nutrient element deficiencies. At the time this work was performed, fertiliser applications were not required to overcome deficiency of the cationic nutrient elements to achieve profitable production. That is, adding cationic fertiliser to these soils usually had no impact on production. The method requires measuring the cation exchange capacity of soils that is balanced by calcium, magnesium and potassium. Then fertiliser advice is provided so as to achieve the desired ratio of these elements balancing the surface charge. The method does not involve measuring production responses to the added fertiliser.
- We now understand that most of the exchangeable $H^+$ that we measure in soils is an experimental artefact; it does not really exist. The exchangeable $H^+$ that was measured resulted from an increase in surface charge density (CEC) as a result of using a high ionic strength saturating solution (commonly 1 M) (van Olphen 1977). With the development of more appropriate methods of measuring cation exchange capacity (e.g. Gillman and Sumpter 1986) exchangeable $H^+$ is not found at measurable concentrations except in the most acid soils (pH water<4.5).

During the 1940s, Bear and co-workers conducted a series of studies at the New Jersey Agricultural Experiment Station investigating the growth of alfalfa (Medicago sativa). As part of this research Bear and coworkers proposed the 'ideal ratio' of exchangeable cations in the soil. Since the publication of these ratios by Bear, it has been assumed by many that optimum plant growth will only occur when these 'ideal' conditions are met. This is despite Bear and co-workers' acknowledgement that maximum growth will occur over a wide variety of cation ratios. In their work, the purpose of providing a high Ca saturation (65%) was to allow maximum growth whilst also minimising luxury K uptake. Indeed, Bear and co-workers logic was as follows: (1) good growth occurs across a wide range of Ca:K ratios, (2) a high Ca saturation percentage limits luxury K uptake, and (3) 'K is a much more expensive element than the Ca which it replaces' (Bear and Toth 1948). Thus, the application of Ca to reduce K uptake was cheaper than applying K which would be taken up by the plant in luxurious amounts. Although split-K applications was considered as a method for reducing luxury K uptake (Bear and Toth 1948), it appears that this practice was never explored in detail.

At about the same time that Bear was conducting his investigations, Albrecht and co-workers were also conducting a series of experiments at the Missouri Agricultural Experiment Station. Much of their research investigated the growth (and $N_2$-fixation) of legumes, and examined the effect of soil fertility on plant palatability and the nutrition of grazing animals. In many of these studies conducted by Albrecht, clay minerals were extracted from the soil, subjected to electrodialysis, then saturated with various cations such as Ca, K, Mg, and Ba [see Albrecht and McCalla (1938)]. By mixing these clays at different ratios, Albrecht was able to investigate the effect of cation saturation on plant growth.

Albrecht concluded that it is important to maintain a high Ca saturation percentage. Indeed, it was this observation which would eventually form the basis for much of Albrecht's concept of the 'balanced soil'. However, it would seem that the design and interpretation of the experiments used to demonstrate the need for a high Ca saturation were often flawed. Based on experiments with soybean (*Glycine max*), Albrecht (1937) concluded that (1) the nodulation of legumes in acidic soils is limited by low Ca concentrations more than by the acidity itself, and (2) plant growth and nodulation increase as Ca saturation increases. In fact, Albrecht later stated that 'plants are not sensitive to, or limited by, a particular pH value of the soil' (Albrecht, 1975) and that 'nitrogen fixation is related to acidity, or pH, only as this represents a decreasing supply of Ca as a plant nutrient' (Albrecht 1939). However, examination of the data of Albrecht (1937) reveals that nodulation is indeed inhibited by soil acidity; nodulation only occurred when the pH was ≥ 5.5, and no nodulation occurred at pH 4.0, 4.5, or 5.0 at any Ca concentration (so Albrecht misinterpreted his own data). According to 'The Albrecht Papers' (Albrecht 1975), Albrecht (1939) demonstrated that for a 'balanced soil', '65% of that clay's capacity (needs to be) loaded with Ca, 15% with Mg'. However, it is unclear how these 'balanced' percentages were derived, as examination reveals that the rate of $N_2$-fixation (measured as the difference in N content between the plant and the seed) increased linearly with Ca-saturation – the greatest fixation actually occurring at the highest rate of Ca-saturation, i.e. 88% (*vs.* the 'balanced' Ca saturation of 65%). Similarly, the work of Albrecht (1937) showed that both plant mass and nodulation rate increased linearly with increasing Ca saturation. Later, and notably after the work of Bear and Graham had been published, Albrecht stated that 'extensive research projects served up this working code for balanced plant nutrition: H, 10%; Ca, 60–75%; Mg, 10-20%; K, 2–5%; Na, 0.5–5.0%; and other cations, 5%' (Albrecht 1975). Whilst it is unclear as to the exact origin of Albrecht's 'balanced soil', it appears likely that it relied, at least to some extent, upon the 'ideal soil' of Bear and co-workers.

That the 'ideal' cation exchange ratio idea received so much attention at the time is surprising, given that, at the same time, other researchers were reporting that it did not work. Hunter and associates in New Jersey (Hunter 1949) could find no ideal Ca/Mg or Ca/K ratios for alfalfa, nor did Foy and Barber (1958) find yield response of maize (*Zea mays*) to varying K/Mg ratio in Indiana. A comprehensive and elegant demonstration of the failure of the approach is presented by the glasshouse and field studies of McLean and co-workers (Eckert and McLean 1981; McLean *et al.* 1983), where Ca, Mg and K were varied relative to each other. They concluded that the ratio had essentially no impact on yields except at extremely wide ratios where a deficiency of one element was caused by excesses of others. They emphasised the need for assuring that sufficient levels of each cation were present, rather than attempting adjustment to a non-existent ideal cation saturation ratio.

One of the reasons that the cation saturation ratio idea has persisted, is that, in very general terms, there is just enough 'truth' in it to make it seem reasonable.

## A calcium deficiency case study

### Calcium deficiency induced through the use of magnesium oxide as a liming material

With the development of a magnesium mining and refining industry in Queensland, the opportunity to use by-product MgO as a liming material became possible, and was considered a practical approach to ameliorating acid, magnesium deficient soils. Dr Kylie Hailes undertook research on this issue for her PhD under the supervision of Dr Bob Aitken and myself. In her work, Kylie investigated amelioration of acidity using MgO, mixtures of MgO and $CaSO_4$ (gypsum), and compared this to lime. She measured short-term root elongation of maize and mungbean as an indication of aluminium toxicity and of calcium deficiency. I have removed the low pH values, where aluminium toxicity will have limited root growth, so that the primary factor influencing root growth is calcium supply. As you can see from the data in Figures 5 and 6, root growth reaches a maximum by 20% calcium saturation of the exchange, or a Ca/Mg ratio of 0.5. Clearly there was no need to reach the 60 to 70% calcium saturation advocated in the 'cation saturation approach'.

Finally, and as an aside on the cation saturation ratio issue, advocates of the cation saturation ratios approach present an 'ideal' situation as being a soil with a pH of 6.0 to 6.5, and a distribution of cations including 12% of the cation occupancy being by $H^+$. To a soil chemist, this really calls into question the credibility of the approach; for the simple reason that it would not be possible for the exchange to have so much exchangeable $H^+$ at this pH. Vietch (1904) recognised at the turn of the century that

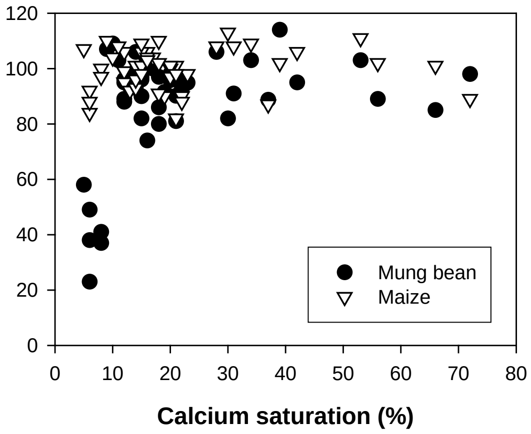

**Figure 5. The effect of Ca saturation on the rate of root elongation (a measure of Ca deficiency) for maize and mungbean in acid soils limed with MgO and mixtures of MgO and $CaSO_4$.**

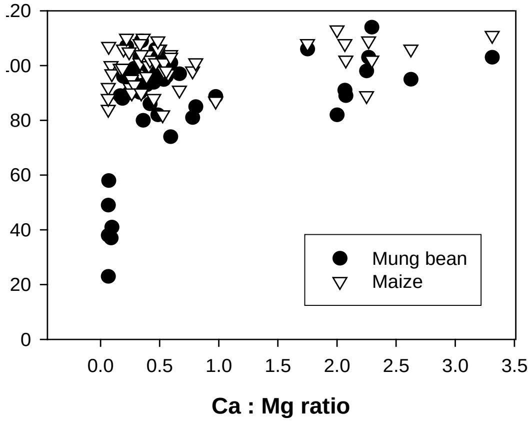

**Figure 6. The effect of Ca to Mg ratio on the rate of root elongation (a measure of Ca deficiency) for maize and mungbean in acid soils limed with MgO and mixtures of MgO and $CaSO_4$.**

acid soils were aluminium saturated, rather than $H^+$ saturated. Indeed, even if you deliberately saturate the exchange of a soil with $H^+$, the acidity dissolves the soil minerals releasing aluminium which occupies exchange sites. So we never find $H^+$ saturated soils. The reason for the high $H^+$ levels reported is the use of inappropriate (and very out of date) analytical approaches. Without going into detail, we now recognise that the amount of cation exchange on a soil varies with the pH and the ionic strength (concentration) of the soil solution. As you increase either the pH or the ionic strength, the soil gets more negatively charged (higher cation exchange capacity), and it does this by loosing $H^+$ from the surface. By measuring cation exchange with concentrated solutions at high pH, you get a cation exchange measurement that is too large, and you incorrectly measure a lot of $H^+$ as being present.

To conclude this section on plant Ca and Mg nutrition I will restate the take-home message I started with;

> The ratio of exchangeable calcium and magnesium in soil will not influence plant growth, except at extreme values seldom encountered in agricultural soils.
>
> and add to it to the conclusion from Lipman (1916) when he reviewed the same topic.
>
> 'I have known of measures employed in soil management in this state, based on theory of the lime-magnesia ratio as first enunciated by Loew and later exploited by unscientific men, which to the rational-minded experimenter in soils and plants, appeared to be the veriest folly'

## Cation ratio effects on physical fertility

The 'ideal' cation balance paradigm also postulates an effect of cation ratios on plant growth through changes in soil structure, in particular, surface-crusting, hardsetting, and decreased hydraulic conductivity (i.e. increased run-off). The high exchangeable Ca content (65%) of an 'ideal soil' is undoubtedly beneficial in maintaining and improving soil structure and aggregate stability (see Amézketa (1999) for a review). However, the concern arises that if the soil Ca content is lower (and the Mg higher) than that recommended by the BCSR, then soil structure may decline. This concern is based on the observation that soil aggregates 100% saturated with Ca are less likely to disperse than those saturated with Mg (Rengasamy 1983). In fact, whilst a 'balanced soil' is likely to have good structure, this structure can be maintained across a range of Ca:Mg ratios – the 'ideal' ratio is unnecessary. For example, Rengasamy *et al.* (1986) demonstrated that structure of a red-brown earth (Rhodoxeralf) (as measured by hydraulic conductivity) was maintained across a variety of Ca:Mg ratios (Figure 7).

These laboratory observations of Rengasamy *et al.* (1986) have been confirmed in the field. In the on-farm trials of Schonbeck (2000), the poor hydraulic conductivity, crusting, and hardpans observed on these soils had often been attributed by the farmers to the cationic 'imbalance' of the soil. However, the reduction in the Mg-saturation from 18–28% to 11–21% had no effect on bulk density (compaction), moisture content, infiltration rate, or soil strength. In addition, the two soils that were the most 'unbalanced' (Mg 28%, Ca 59%) actually had the best physical properties.

## Biological fertility

The provision of 'balanced' cation ratios has been claimed to improve the soil's biological fertility, and decrease weed growth and insect attack. Indeed, Albrecht (1975) stated that 'more fertile soils prohibit insects'. However, comparatively little information is available comparing the biological fertility in 'balanced soils' to that in soils containing other cationic ratios. Nevertheless, in the trials of Schonbeck (2000), a reduction in Mg-saturation (from 18–28% to 11–21%) had no detectable effect on soil organic matter, biological activity, abundance of weeds, or incidence of disease or insect pest damage, when compared to the control treatment. Similarly, Kelling *et al.* (1996) concluded that variation in the Ca:Mg ratio had no significant effect on the earthworm population or on the growth of weeds (grass or broadleaf).

## How should a producer respond?

- Where the 'science' is not complete, predicting benefits is hard or even impossible.
- Your situation is unique.
- Test the product yourself.
- But test it properly – comparison with established alternative; replication.
- Do not fool yourself.

All easier said than done, but how would you practically go about testing the effectiveness of a microbial inoculant designed to fix N or solubilise P? How would you ensure that you could draw valid conclusions – i.e. not fool yourself? Here are a few simple guidelines that might be useful in formulating your on-farm experiments.

Obviously, the work needs to be done in the field, with all the system buffering and spatial variability that brings with it. Replication is therefore essential, as is a random allocation of treatments to strips or plots. Strips are often

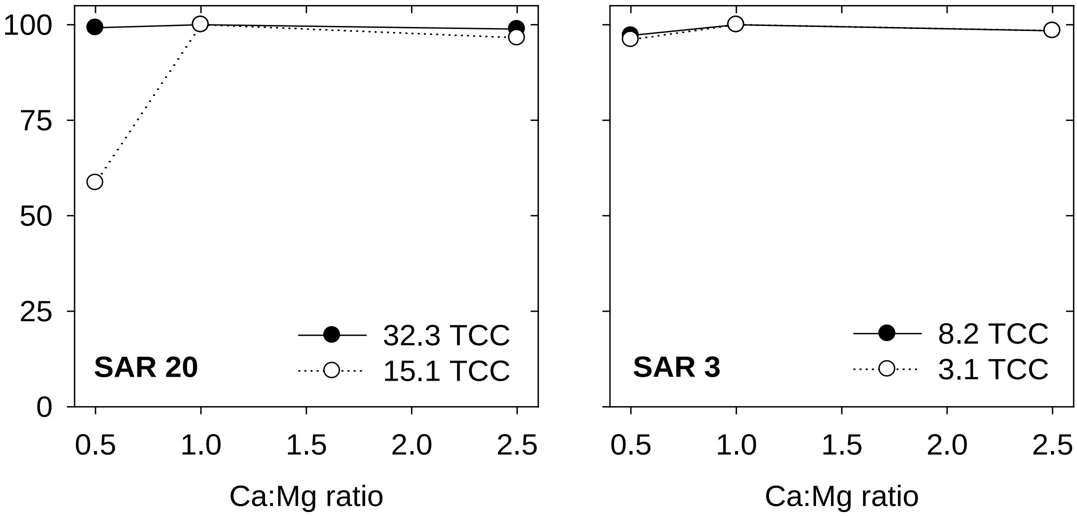

**Figure 7. Effects of the Ca:Mg ratio, sodium adsorption ratio (SAR), and salinity (presented as the total cation concentration (TCC, $mol_c$/L) on the relative hydraulic conductivity of a surface soil of a sodic red-brown earth (Rhodoxeralf). The relative hydraulic conductivity has been calculated separately for each TCC series. Data are from Rengasamy *et al.* (1986).**

easier to manage, especially with GPS guidance systems are available. The important thing is to at least match the strip/plot width to that of your measuring or harvesting equipment, because that is the operation which needs to be easy to do (and do well) to measure the treatment effects. How many times have pasture or crop yields from strips not been collected because the harvest was rushed, or proved too difficult or laboursome to collect! If you cannot measure it, how do you expect to manage it.

The next thing to consider is your reference treatment or control, so that you can interpret the research findings. Ideally it should be something you do currently, and not a 'nothing applied' treatment (or not only a nothing applied treatment), as you are generally trying to prove the treatment is as good as, or better than, what you are currently doing (or cheaper). Every time produce leaves the farm, be it a truck load of beef, lamb, crop or wool, soil nutrition is driving out the gate and being removed from the farm. Monitoring that removal, and replacing it when required, is the only valid way of providing a truly sustainable and productive farming operation.

Also, be very clear about what you are trying to test, given the cautionary examples listed earlier. I think most people would accept that many of our current fertiliser use guidelines are best bet options, *albeit* based on experience gleaned from lots of trials and experience in different farms and soil types. That means that a low pre-plant soil N or P test does not guarantee you a fertiliser response. Make sure that you don't just have two comparisons in your test – a current practice (e.g. your standard rate of starter P) and your biological alternative or treatment of interest. If they produce similar yields you will not be any wiser, as the product could be effective, or the site may not have been responsive in the first place. Having a nil P treatment in this case will sort that out.

Finally, do not leap in without giving the product a thorough test in different seasons and paddock conditions. People often question why science takes so long to be sure about something, but the earlier *P. bilaii* example shows that there will be a range of outcomes with an average effect, and it is important to test often enough to get a realistic estimate of that average effect before you make a change.

Knowing if you are indeed responsive to a nutrient, or a combination of nutrients, is critical before you invest. Many, many dollars have been spent applying various products to paddocks and soils that do not have a deficiency, and thus have had not made any difference, except to the hip pocket. Do not be the next to do that again! Test, understand, and seek advice.

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