Ministry for Primary Industries
Manatū Ahu Matua

Nutrient Management Science – State of Knowledge, Use and Uptake in New Zealand

MPI Technical Paper No: 2013/59

Prepared for the Ministry for Primary Industries

By the Soil and Land Use Alliance

18 June 2013

Enquiries to:
Tim Payn: tim.payn@scionresearch.com

Lead Authors:
T. Payn[3], M. Beare[4], M.Shepherd[1], K. Bayne[3]
Contributing Authors: N. Botha[1], A. Collins[2], D. Curtin[4], M. Davis[3], P. Fraser[4], C. Hedley[2], C. Hoogendoorn[1], P. Johnstone[4], G. Lucci[1], R. Parfitt[2], J. Xue[3]
Knowledge Navigators:
J. Barr[1], M. Gee[4], J. Toplak[3]
Project Manager:
A. Brockerhoff[3]

[1]AgResearch, [2]Landcare Research, [3]Scion, [4]Plant & Food Research

ISBN No: 978-0-478-42320-4(online)
ISSN No: 2253-3923(online)

2013

Growing and Protecting New Zealand

Disclaimer

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries website at
http://www.mpi.govt.nz/news-resources/publications.aspx

Contents

Page

EXECUTIVE SUMMARY

New Zealand's primary sector contributes very significantly to exports and to its Gross Domestic Product, with combined export revenues of $29bn in 2012 for dairy, meat and wool, forestry and horticulture, and 12.1% of GDP in the year ending March 2011. Nutrients are the single biggest operational expenditure item on farms. The application of nutrient management science (NMS) therefore plays a significant role in New Zealand's ability to generate these export revenues. Furthermore, on-going development and effective use of NMS is essential if New Zealand is to meet the dual challenges of improving on-farm profitability and decreasing nutrient loss to the wider environment.

Given the very significant investment in NMS in past years, the Ministry for Primary Industries (MPI) commissioned a review of NMS for the period 1998 to 2013 to take stock of progress and to identify priorities for future work. The focus of the review was on: science advances that had been achieved; how effectively these advances had been implemented across the primary sector; and where the 'knowledge frontiers' were for NMS. Gaps and priorities for future work were to be identified within the context of the national and international environment and recommendations made. The resultant project therefore comprised three components: a review of international trends in NMS; an appraisal of the national research carried out in the last 15 years; and a review of use and uptake (or the implementation pathway) for NMS. Key findings from these reviews were used to develop a gap analysis and series of recommendations for areas of focus that would result in increased effectiveness of use of NMS and ultimately improved nutrient management practice across New Zealand's primary sector.

International trends and key drivers

A review of international trends in NMS and key drivers relating to NMS such as climate change, fertiliser technologies was undertaken to place the national review in context. It was concluded that, internationally, demand for food will increase and will ensure continued markets and opportunities for New Zealand Agriculture. Risks to food and fibre production will increase as a result of climate change, and it is likely that fertiliser costs will continue to rise. Concerns about the sustainability of agriculture and forestry systems will lead to more demand for green certification of products, and reduction or mitigation of environmental impacts. International NMS research focus is on increased nutrient use efficiency, enhanced production and lower environmental footprints. These global trends are all directly relevant to NZ and will require a response.

Progress nationally in NMS

A national review assessed science advances in each of the primary sectors (arable, dairy, forestry, horticulture, sheep and beef), and across New Zealand regions, soil orders, key soil processes (e.g. leaching, erosion, denitrification), and nutrient sources. This was undertaken by a thorough literature analysis, with over 1900 references captured. The focus of the review was predominantly on nitrogen (N) and phosphorus (P).

NZ agriculture is different to other parts of the world in many respects because of its heavy dependence on the pastoral sector and, consequently, the animal is the source of much of the nutrient leakage (nutrient inefficiency) in the NZ system. Furthermore, the dairy production system is quite different to systems in, for example Northern Europe because it has evolved to operate in an unsubsidized environment. The challenge for New Zealand is operating profitable production within the constraints of world market prices. The challenge for NMS is therefore to assist in the design of nutrient efficient production systems that are economically, as well as environmentally, sustainable. Our assessment of research in New Zealand to date is that the focus has been on this; the continuing challenge is being able to achieve this under increasingly tight environmental demands.

The scope of the research carried out in last 15 years has reflected the needs of the sectors as they emerged; consequently, topics have been varied and broad. The result is effective coverage of topics within both the N and P cycles. Progress has built on the considerable amount of research done prior to the 15 year period covered in this study. Overall, the knowledge base available to farmers, foresters and horticulturalists (FFH) today is very sound. We are well placed to meet future challenges.

There are numerous examples of where Nutrient Management Science has had a significant impact on practise, such as:

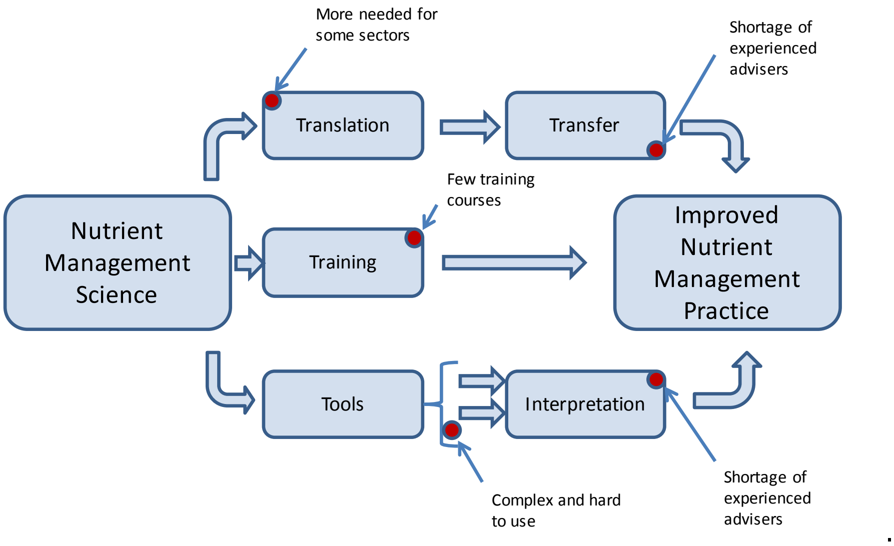
- Development and adoption of Best Management Practices – for example, farm dairy effluent application and management
- Forestry fertiliser management systems have been adopted across at least 80% of the national planted forest estate
- Rapid growth in the development of paddock scale and whole farm system models. The OVERSEER® Nutrient Budgets model is probably the best known example. These models have been able to capitalise on the NMS research base to model nutrient cycling at the farm scale, thus aiding the development and implementation of strategies to improve nutrient use efficiency.
- Development and adoption of a wide range of Decision Support Systems across all sectors based on many field based experimental programmes.
- Process inhibitors – New Zealand is a world leader in the use of process inhibitors to manage N cycling, most notably through the direct application of DCD to soils to reduce N loss.

A range of knowledge frontiers and critical gaps were identified across the sectors. These include matching crop nutrient demand and supply patterns, spatial and temporal variation in urine patch N dynamics, incorporation of economics into models and decision support systems, managing the increasing complexity of farm systems and increasing regulatory requirements, improving nutrient use efficiency (especially P), legumes as a source of N, N mineralisation predictors, more integrated nutrient management tools, and the overall implementation pathway for NMS.

National science capability and capacity and associated infrastructure are important to maintain momentum in the development of NMS. Good interaction within the science community, multidisciplinary approaches and maintenance of a balanced science demographic is crucial (currently the latter is skewed towards an older age cohort of scientists). Maintenance of long term science infrastructure such as long term experiments (e.g. Winchmore - pastoral, Puruki - forestry) has been shown to be invaluable

Use and uptake of NMS

Use and uptake of the science was reviewed through interviews with key stakeholders. A number of key findings and issues around use and uptake (or the implementation pathway) for NMS were identified. Views ranged from the perception that the pathway was ‘broken’, to that it worked well. The body of knowledge and tools available to farmers, foresters and growers and their advisors is large. However, use and uptake is variable. Improvements targeted at the highlighted areas in the figure below would lead to improved nutrient management practice.

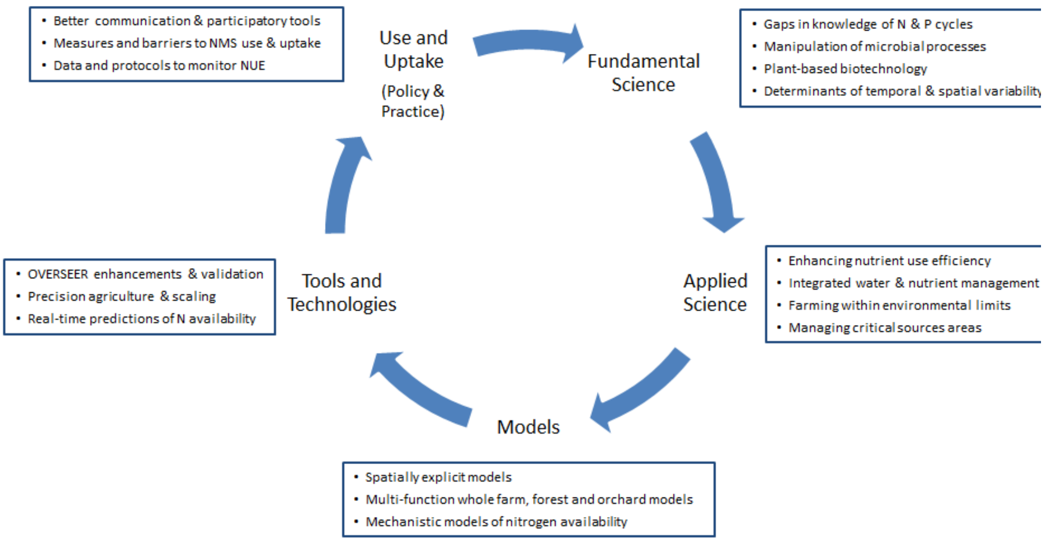


Nutrient Management Science implementation pathway

Farmers, foresters and growers depend on experienced and trusted advisers, but these are in short supply. The type of knowledge and tools practitioners require also does not currently match that available. Users are looking for simple, easy to understand information. Models are often seen as complex and hard to use, and needing increased economic components. Additionally, there was concern that models were not being used appropriately in some instances. When discussing use and uptake, interviewees focused far more on human interaction rather than models and software.

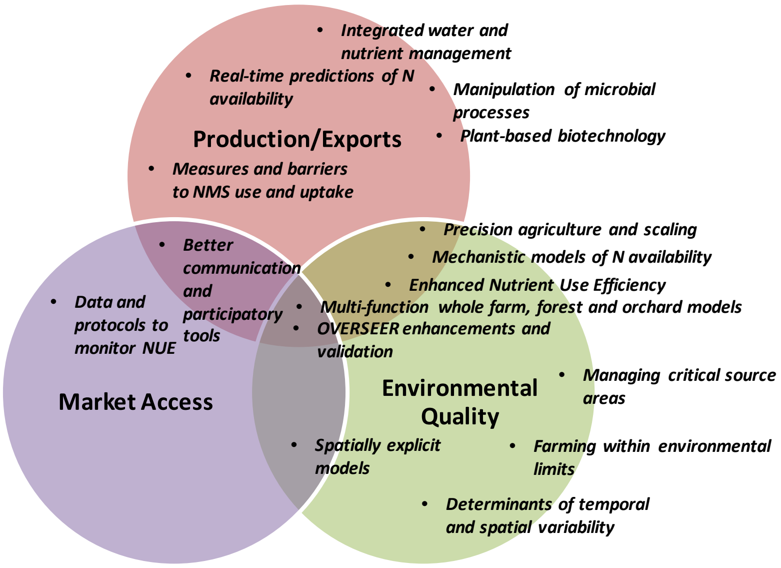
Knowledge frontier

The knowledge frontier varies depending on sector. A number of priority areas were identified for focus of future investment. These were categorised within the cycle of science, technology, and uptake (fundamental science, applied science, models, tool and use and uptake). Priorities are summarised in the following diagram.



Recommended Priority Research Areas

Overall these priority areas contribute strongly to the New Zealand context of Green Growth and the Business Growth Agenda (Building Export Markets and Building Natural Resources) through three key outcomes: increased production/exports; green market credentials/market access; and maintaining and enhancing environmental quality.



Mapping priority research areas to key outcomes

There is a fairly even balance between priorities focused on production (business growth agenda – exports) and environmental quality (business growth agenda – natural resources), but fewer on market access. We conclude that to underpin Green market credentials/market access, there are a number of research areas to be explored in the area of benchmarking nutrient inputs and measures of the nutrient footprint or nutrient use efficiency (now a major global agriculture indicator). There are currently no readily available data on this across the New Zealand primary sector to support assertions of environmental credentials.

Additionally, national science and technology capability will need to be maintained and further developed to support these priorities. There is an ageing science demographic in New Zealand with some gaps in national capability in the extension/technology transfer area.

INTRODUCTION

New Zealand's primary sector contributes very significantly to exports and overall to its Gross Domestic Product with combined export revenues of $29bn for dairy, meat and wool, forestry and horticulture in 2012 (MPI 2012) and 12.1% of GDP in the year ending March 2011 (MPI 2012). Nutritional Management plays a very significant role in New Zealand's ability to generate these export revenues.

PROJECT NEED

Discussions with MPI stakeholders have highlighted the investment spent on research in Nutrient Management Science by the Ministry of Business, Innovation and Employment (MBIE) and the Ministry for Primary Industries (MPI) with uncertain outcomes from this research. Recent cabinet papers on the water reforms have sought information on research to date as it affects water quality as well. This has raised the question of what has been researched, and how effectively the results have been used. As nutrients are the single biggest operational expenditure item on farms, effective use of research knowledge is important and may save significant expenditure and improve on farm profitability.

Discussions between MPI and stakeholders identified that Nitrogen and Phosphorus were the key elements of interest, and that the project should review research and use across the primary sector (Arable, Dairy, Forestry, Horticulture, and Pastoral land uses).

PROJECT OUTCOME

The expected benefits and outcomes from this project should place MPI in a better position to target advice and policy on nutrients and nutrient management to stakeholders and research funding agencies including MPI. MPI should be able to provide information on knowledge frontiers and identify gaps and areas of acceleration that will be most useful to stakeholders and policy. It will also partially contribute to the Water Team needs.

PROJECT APPROACH

A review project was designed to address the topic as outlined above (project outline is contained in Appendix 2). The project was undertaken in four phases 1: a brief review of international trends in Nutrient Management Science (NMS), 2: national developments in NMS for the period 1998 to 2013, 3: an evaluation of the uptake and effectiveness of use of the research, and 4: a synthesis and discussion of the findings and evaluation of the gaps and knowledge frontiers with some recommendations for future directions in research.

Nutrient Management science is undertaken in New Zealand by a mix of Crown Research Institutes (CRI), Universities, Polytechnics, and Private companies. Research and knowledge translation and transfer is undertaken by these agencies but also by dedicated technical farm advisors and consultants supported by associations such as the Fertiliser Association (www.fert.org.nz).

A project team was established by the Soil and Land Use Alliance, a four CRI grouping of AgResearch, Landcare Research, Plant and Food Research and Scion. The team established was multidisciplinary and contained specialists with NMS experience in all 5 primary sector land uses, all aspects of nutrient management science in New Zealand, plus social scientists with experience in research use and uptake.

The project scope was designed as a nested matrix of topics to be reviewed:

- Nutrients (N, P, other where appropriate)
- Nutrient sources (e.g. fertilisers, amendments, effluent)
- Soil Processes/Impacts/Interactions, (things that affect ability to give good management advice – e.g. leaching, soil microbial processes)
- Spatial Environmental Framework (soil orders, regions)
- Outcomes
    - Productivity
    - Environmental Impacts
- Sector specific issues (arable, dairy, forestry, horticulture, pastoral)

The project was undertaken over a four month period from March to June 2013. This timeframe and the resources available determined the methodological approach as outlined below and in more detail in the body of the report.

BRIEF METHODS

International Review:

A brief review of international literature was undertaken to understand global trends in NMS and associated technologies. Particular focus was placed on N and P and on NMS for both increasing productivity and minimising environmental impacts.

National Review:

This part of the review was segmented at a number of levels to cover the primary sector crops and New Zealand's environment. The New Zealand literature was summarised, including both peer reviewed scientific articles and the grey literature such as technical reports. Brief state of knowledge summaries were developed for each segment. A gap analysis was developed, based on the state of knowledge, perceived scale of need by sectors and reflecting on international trends. This allowed us to develop a view of opportunities for improvement to NMS in NZ.

Use and Uptake:

We used a targeted interview and survey approach with 35 representatives of selected stakeholder groups (industry associations, fertiliser companies, councils and other agencies and groups, and farmers, foresters and horticulturalists) to determine what of the science knowledge is being used, how it is delivered to stakeholders (e.g. tools, professional advice) and how effective the application of the knowledge is. We then synthesised the findings from the interviews and survey and determined the current state of use and uptake, where gaps occur, and areas to focus on to enhance wider use of the knowledge.

Discussion and Recommendations:

This section identifies the knowledge frontier and gaps and recommendations for improvements, as well as state of knowledge and areas for best practice. Key findings from the international, national, and use and uptake review were summarised. Knowledge frontiers and critical gaps were identified by the team. This analysis was used within an outcomes framework developed based on national green and business growth agendas to identify priority areas for future research and technology transfer focus. This was presented in the context of a research 'wheel' that included fundamental and applied science, models tools and technologies, and use and uptake mechanisms.

INTERNATIONAL TRENDS IN NUTRIENT MANAGEMENT SCIENCE

REVIEW METHODS

The international research literature on N and P is vast, so we restricted our analysis to a high level review that identifies global trends in research including nutrient use efficiency (NUE). Given the time constraints we relied heavily on the review by Sutton et al. (2013). To inform the national analysis we focussed on understanding the drivers (such as population growth, climate change) and trends affecting NMS globally and then identified the key research trends that were a response to these drivers. The review was undertaken as a desk based exercise with supplementary discussions with experts through the team's national and international networks

FINDINGS

INTERNATIONAL DRIVERS AFFECTING NMS RESEARCH

The legacy of the 'green revolution' - the role of Nitrogen and Phosphorus

Nitrogen (N) and phosphorus (P) are key yield-limiting nutrients. It has been estimated that up to one-half the world's population is fed today because of the increased agricultural production that has been achieved using N and P fertiliser (Figure 1). Scientific advances in the late 19th century and first half of the 20th century, including development of the Haber-Bosch process and the process to make superphosphate, laid the foundation for the 'green revolution' from the 1950s when use of N and P fertilisers increased rapidly. Between 1950 and 2000, estimated mineral fertiliser N use increased from 4 to 83 Mt per year, while P fertiliser use increased from 3 to 14 Mt. The ratio of biologically fixed N (BFN) to fertiliser N decreased from 14:1 in 1900 to 6:1 in 1950 and, by 2000, the input of fertiliser N was about double that of BFN (Bouwman et al., 2011). This massive input of nutrients enabled the world population to expand rapidly, while simultaneously increasing per capita consumption. Increased livestock production, to meet the growing demand for animal protein (global per capita meat consumption has doubled since about 1960), has also had a significant impact on the use and cycling of N and P. In the European Nitrogen Assessment, it has been estimated that 85% of harvested reactive N (Nr) is used to feed livestock, with only 15% feeding people directly, while the average EU citizen consumes 70% more protein than needed for a healthy diet. Annual global manure production (92 Mt N) is estimated to have increased by a factor of 3 since 1900, and is projected to increase by a further 50% by 2050. While recent trends in nutrient consumption are relatively stable in developed countries, growing human population and per capita meat/dairy consumption are causing a rapid increase in nutrient consumption in developing countries. It is anticipated that these countries may account for ¾ of global nutrient consumption by 2050, contributing to a further increase in global nutrient production of 40% to 50%.

It is expected that world population will pass 9 billion by 2050, and that to support this population food production will have to increase by 70% over current levels. This will put extreme pressure on agricultural systems.

Climate Change

Changes in the global climate and weather patterns are expected to have very significant impacts on agriculture and forestry both in terms of production levels but also risk from extreme events. Significant research is underway which will be of relevance to NZ.

Environmental Impacts

High levels of nutrient use are a concern in several parts of the world, especially in Europe, North America, South and East Asia and parts of Latin America. The efficiency of nutrient use can be low and both N and P may be lost to the environment, wasting the energy used to produce/transport fertiliser, and causing pollution through emissions of the greenhouse gas nitrous oxide (N_2O) and ammonia (NH_3) to the atmosphere, plus losses of nitrate (NO_3), phosphate (PO_4) to water. Oversupply of nutrients, or imbalance between nutrients, reduces the efficiency of use. Efficiency is further reduced by including livestock in the food chain, substantially increasing N and P pollution levels. Burning fossil fuels produces a significant amount of reactive N (~20% of human N_r production) which is emitted as nitrogen oxide (NO_x), contributing to particulate matter and ground-level (tropospheric) ozone, which adversely affect human and ecosystem health,. Some thresholds for human and ecosystem health have been exceeded due to N_r pollution. Each of these environmental effects can be magnified by the ‘nitrogen cascade’, where a single atom of N_r can trigger a cascade of negative environmental impacts.

Access to N and P supplies

In Africa, Latin America and parts of Asia there are still large regions with severe nutrient limitations. Inability to replace nutrients removed by harvested crops leads to depletion of soil nutrients and organic matter, reducing soil quality and increasing the risk of land degradation.

The large differences in nutrient use (kg of fertiliser N-P-K per hectare of arable land) between regions – from about 10 kg/ha in Sub-Saharan Africa to over 400 kg per/ha in East Asia (2010/11 data) – can be seen in Figure 2. For developed countries, fertiliser inputs were highest during the 1980s, with a reduction of about 20% in the 1990s (related to efficiency improvements), while application rates have been relatively stable in the last decade. The major contribution to the global increase in nutrient consumption in recent decades has been from developing countries. In 1980, developed countries (including transition economies) consumed around 70% of the global total but, by 2010, the situation had reversed, with the developing economies consuming 70%. The bulk of the expected increase up to 2050 is also anticipated to be used in developing countries.

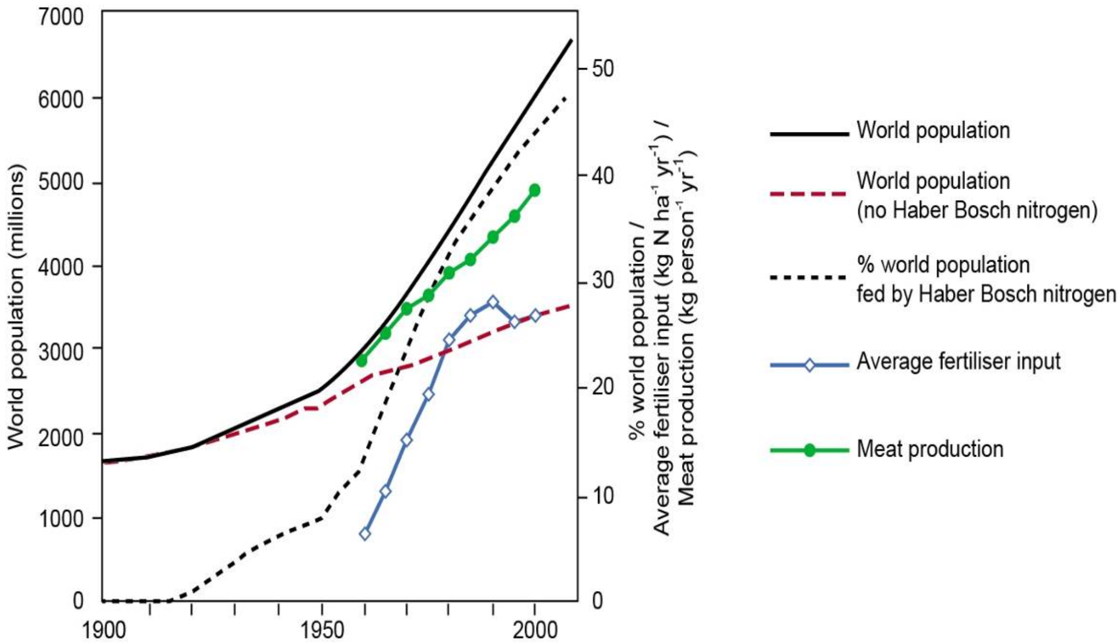


Figure 1 Changes in world human population as compared with estimated changes in the absence of Haber-Bosch nitrogen, showing parallel changes in average mineral Fertiliser input and per capita meat production (Erisman et al., 2008).

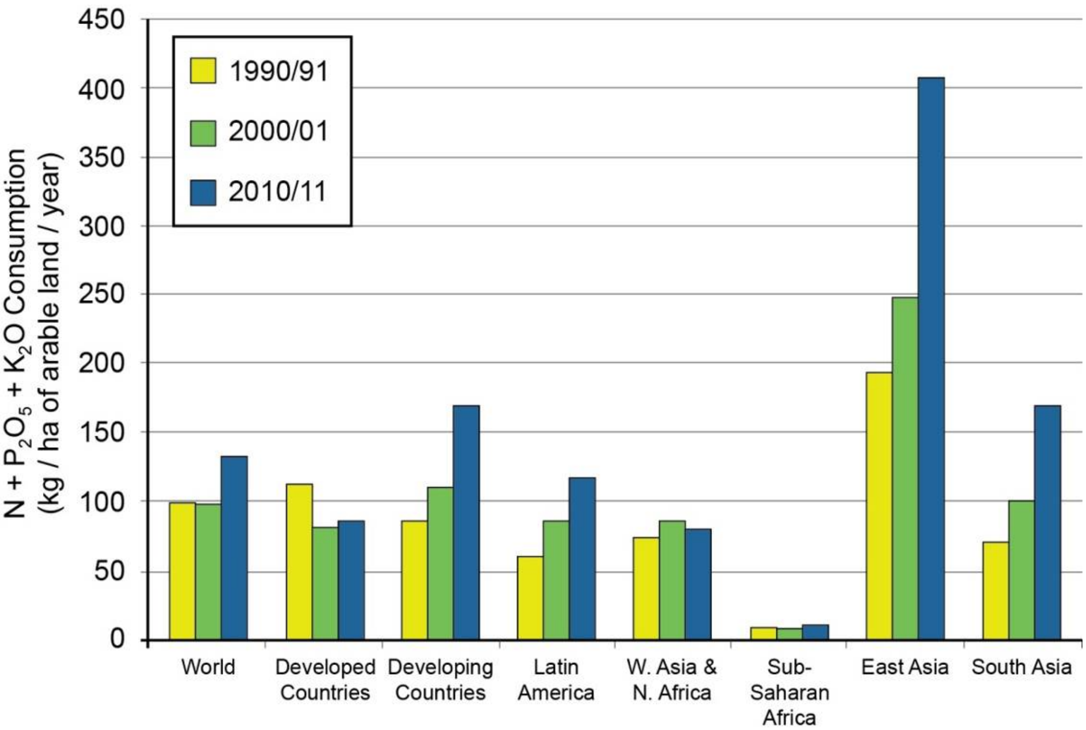


Figure 2. Total annual Fertiliser consumption for different world regions, expressed per hectare of arable land (sum of N, P and K as kg N + P_2O_5 + K_2O). IFDC Graphic derived from FAO data.

Scientists are concerned that world's N and P cycles may now be seriously out of balance, causing major environmental, health and economic problems (Sutton et al 2013). There are major differences between the issues relevant to N and P. Nitrogen represents an especially complex challenge because of the way in which it 'cascades' between different N_r forms, such as NH_3, NOx, NO_3, N_2O, organic N, leading to a multitude of different effects in the environment (Galloway et al., 2003). These include threats to water pollution, air quality, greenhouse gas balance and climate, ecosystems and biodiversity and soil quality. In the case of P, the focus has been on the scale and accessibility of reserves of phosphate rock and on the effects of inefficient P use for water quality (Sutton et al 2013). The central debate for P in recent years has been whether or not depletion of the world's P reserves will jeopardize world food security in the 21st century (Cordell et al., 2009; Syers et al., 2008). Regardless of whether or not "peak P' is a real issue, there is a clear need for more efficient practices that waste less P and minimize its environmental impacts.

GLOBAL TRENDS IN NMS (N&P) – RESPONSE TO THE DRIVERS

Increasing Productivity

In response to increases in demand, productivity increases are being sought, but not just simply through addition of increasing amounts of N and P to increase biomass production. All aspects of nutrient management must be considered to achieve this– responses, cost of nutrients, environmental impacts so while the outcome will be increased production the means of achieving it is composed of a range of components. The term sustainable intensification is increasingly used in agricultural circles – increasing production while maintaining or enhancing the environment. To achieve this, the following topics are high profile internationally.

Promoting nutrient best management practices

The components of a good nutrient stewardship strategy can be summarized as "the 4Rs" (the ***R****ight Fertiliser*, the ***R****ight amount*, the ***R****ight time* of application and the ***R****ight placement*) (http://www.ipni.net/4R).The 4R concept, which been widely promoted internationally, is based on global principles but these principles need to be implemented as a function of local, site-specific conditions, and with full consideration of the available nutrients in soils, animal manures, crop residues and wastes . Improving crop NUE requires the optimization of all critical factors. For a given region, temperature and rainfall are defined, but selecting the appropriate cultivar and choosing the right planting density and time is of paramount importance to achieve the yield potential. Next, water and essential nutrients need to be supplied in adequate amounts, depending on the requirements of the crop and the native supply from soil and atmosphere. Finally, appropriate crop husbandry with integrated weed, pest and disease management can make a difference.

Nutrient use efficiency is often low because of either shortages of one or more essential nutrients or oversupply of one or more nutrients. The first situation often occurs in sub-Saharan Africa due to low soil fertility and lack of resources for buying fertilisers. Oversupply can occur where fertilisers are subsidized, such as in China, and where livestock is kept at high density, so that the animal manures produced cannot be utilized efficiently, such as in parts of Europe and the USA (Sutton et al., 2013).

Nutrient use efficiency

Improving nutrient use efficiency in crop production is a 'win-win' strategy, as it aims at increasing crop production and optimizing the use of external resources. It thereby contributes to food security and to minimizing nutrient losses and eutrophication. Nutrient use efficiency represents a key indicator to assess progress towards better nutrient management. An aspirational goal for a 20% improvement in N use efficiency (NUE_N) by 2020 was proposed by Sutton et al. (2013). This could potentially produce an annual saving of ~20 million tonnes of N along with improvements in human health, climate and biodiversity valued of US$170 billion per year. The N savings (kg/ha) resulting from a 20% improvement in N use efficiency are shown in Fig. 3 for different regions.

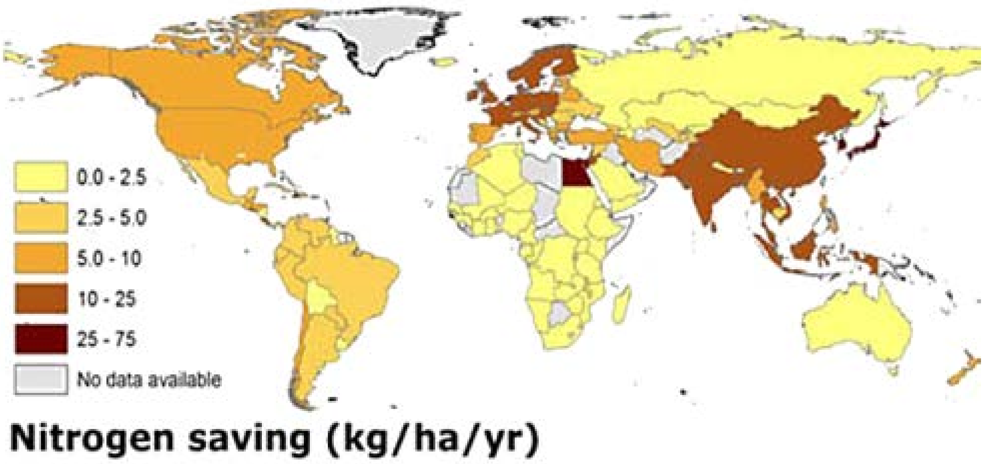


Figure 3. Nitrogen saving associated with improved Nutrient Use Efficiency (NUE). The map shows the Nr savings that would be made, per ha of agricultural land, from a 20% relative improvement in full-chain NUE (Sutton et al., 2013)

The global challenge is to produce enough food for the ever-growing population and at the same time minimize the loss of N to the environment. The global average NUE_N has remained relatively stable at 50-55% between 1987 and 2006. However, improvements in NUE_N have been shown in a number of regions including Europe and North America. European estimates (Brentrup and Palliere) suggest that N use efficiency has increased from around 40% in 1987 to more than 60% in 2006. This improvement was attributed to use of better management practices. Since 1980, agriculture in Denmark has been able to reduce its N surplus by ~40% while maintaining crop yields (Hansen et al., 2012). As a result, significant reductions in groundwater nitrate concentrations have been achieved.

There has been substantial improvement in fertiliser N use efficiency in corn (maize) in the USA . In 1980, a kilogram of N fertiliser produced 42 kg of maize while, in 2000, it produced 57 kg, an increase of over 35% (Figure 4). For the 27 major crops grown in the USA (95% of total crop production), N removal in harvested product increased by ~35% from 1987 to 2007 (Figure 5). As fertiliser N use experienced a smaller increase, the N removal-to-input ratio increased over time, albeit at a slow rate. In contrast, there has been a decline in N use efficiency in China from 32% in 1980 to 26% in 2005 (Ma, Velthof *et al.* 2012). Over that period, fertiliser N inputs increased considerably, but losses to air and water also increased greatly, especially in south, east and central China.

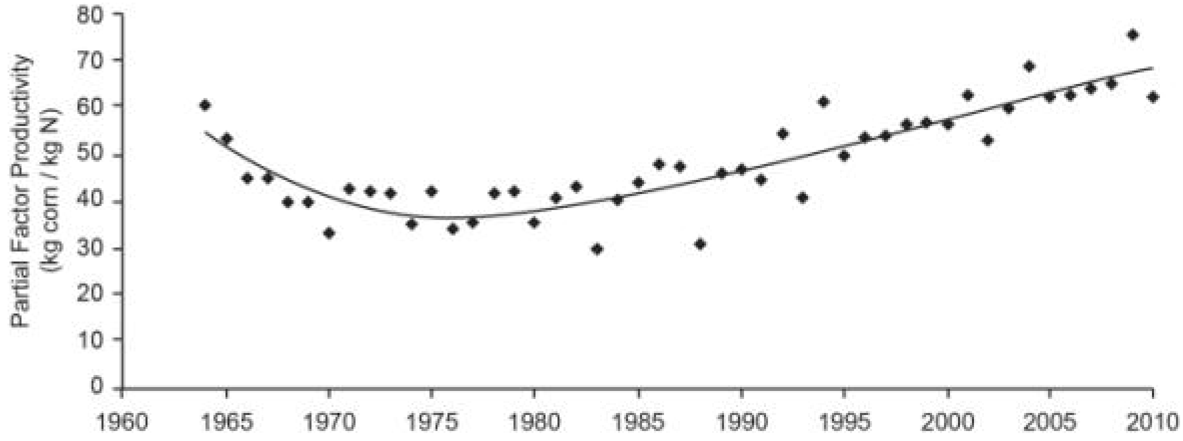


Figure 4. N use efficiency of maize grown in US, 1965-2010 (R. Norton. Presented at meeting of Crop Science Society of South Australia; 20 February, 2013).

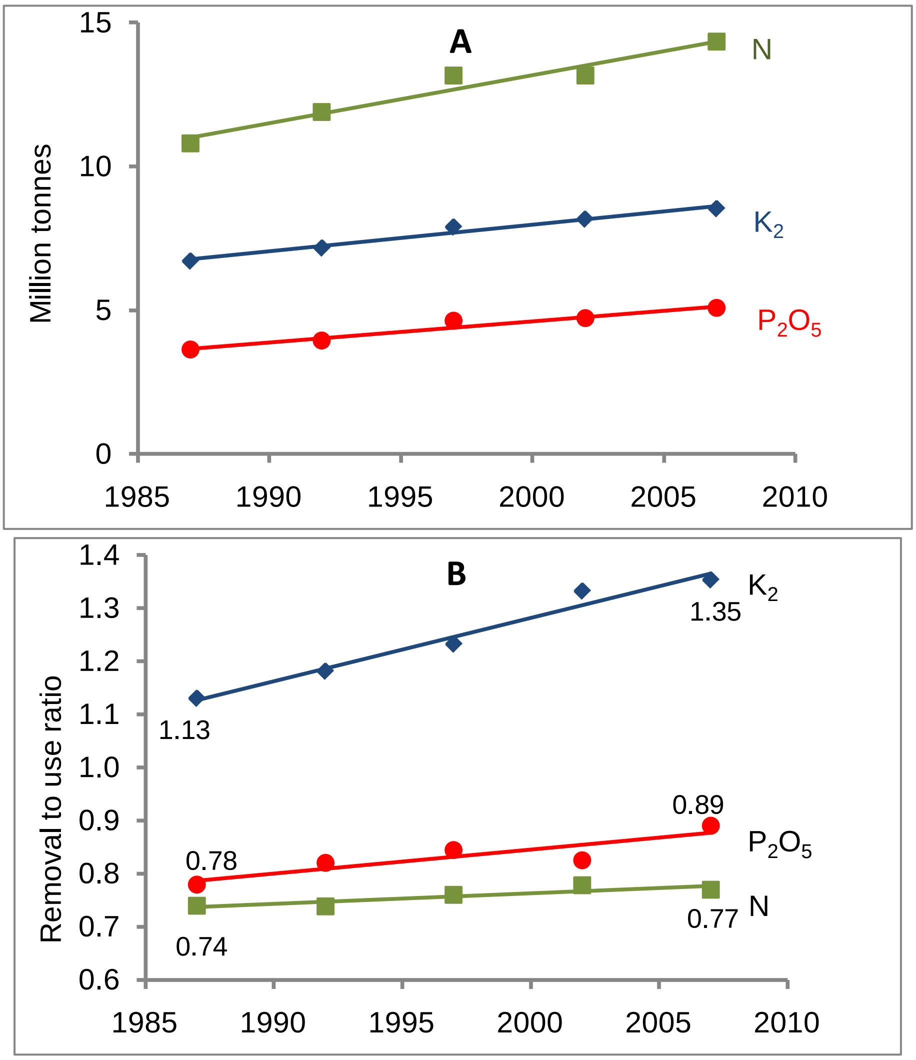


Figure 5. Nutrient removal in crop harvest (A) and nutrient removal to use ratios (B) for the U.S. over a 20-year period (re-drawn from Fixen et al. http://www.ipni.net/nugis).

In intensive agriculture, P inputs in fertiliser can significantly exceed removals in products, i.e., there is a P surplus or positive P balance (Syers et al., 2008). In almost all European countries, the P surplus has been greatly reduced in the past 15 years, associated with decreasing fertiliser P inputs over time (Schroder et al. (2010)). An improvement in P use efficiency in US crop production is also indicated by the data in Figure 5, which show that the ratio of P removed by crop harvest to P inputs (fertiliser- and manure-P) has increased for 0.78 to 0.89 over the 20-yr period to 2007. The high P removal-to-use ratios achieved in the 1990s (>0.8) suggests that P was used efficiently in US cropping systems.

Imports of P into New Zealand in fertiliser and food (211,000 tonnes in fertiliser and 6,000 tonnes in food in 2001/02) substantially exceed exports in produce (41,000 tonnes annually; 2001/02 data). The net import of P, expressed on a per capita basis, provides a metric to assess how reliant a country is on imported P (Cooper and Carliell-Marquet, 2013). Based on the data above, the annual net import value for New Zealand is about 44 kg P/capita. This is extremely high compared with other countries that are dependent on imported phosphate rock for fertiliser production. For example, the net P import value for the European Union (EU15) is 4.7 kg/capita and for Japan it is 5.9 kg/capita. The national P use efficiency, calculated by dividing P outputs by P inputs, was about 20% in 2001/02, which is lower than in other developed countries (commonly > 50-60%; Cooper and Carliell-Marquet, 2013). As fertiliser P consumption has declined since 2001/02 (currently about 150,000 t per annum) some improvement in P use efficiency will have occurred in recent years.

According to Richardson et al. (2011) it may be possible to improve P use efficiency by manipulating plant characteristics, i.e., (i) root-foraging to improve P acquisition by lowering the critical P requirement of plant growth and allowing agriculture to operate at lower levels of soil P; (ii) P-mining to enhance the desorption, solubilisation or mineralisation of P from sparingly-available sources in soil using root exudates (organic anions, phosphatases), and (iii) improving internal P-utilisation efficiency through the use of plants that yield more per unit of P uptake. The potential for manipulating root physiological traits or selecting plants for low internal P concentration has yet to be realised (Richardson et al. 2011).

Microorganisms play an important role in mediating the availability of P to plants and examples of microbially mediated P mobilization by different microorganisms have been reported (for review, see Richardson, 2001; Gyaneshwar et al., 2002; Khan et al., 2007;; Harvey et al., 2009; Richardson et al., 2009; Zaidi et al., 2009). However, despite considerable promise microbial products for P mobilisation have not had major application to broad-acre farming systems.

Research is underway to recover P from waste streams and reuse P, to optimise of land use, prevent erosion, improve fertiliser recommendations and placement methods, improve genotypes and promote mycorrhizae, recycle manure to P deficient lands, and adjust livestock diets *(*Schröder et al 2010).

Technologies

Precision agriculture

As soil available nutrients can show considerable variability, even over small spatial scales, there may be potential to improve the efficiency of fertiliser use by adjusting the application rate depending in the nutrient supplying capacity of the soil. Although the technologies to implement variable rate fertilisation (e.g., GPS positioning, yield monitors, variable rate applicators) have been available for more than a decade, adoption has been limited, internationally. For example, a survey in the major grain-growing regions of Australia showed that 20% of growers had adopted some form of variable rate fertilisation by 2008 (Robertson, Llewellyn *et al.* 2012). However, the adoption rate was up significantly from the <5% found in a survey 6 years previously.

Split N applications
Splitting fertiliser applications, particularly where the N requirement is high, is an accepted practice to improve efficiency by reducing losses to the environment. In the UK, the HGCA provides detailed guidelines on how N applications should be timed to maximize use of N for grain and protein production in wheat crops (HGCA, 2009). Similar guidelines will be available elsewhere.

Decision support systems and aids
There have been rapid advances both in computer technologies and computer-based decision support systems. Generally the focus has been on spatially based management systems underpinned by scientifically based models. Tools are generally very regionally specific in their detail.

Soil fertility tests have not changed significantly in the past two decades. Some new laboratory N tests [e.g., Illinois Soil N test (Mulvaney et al., 2006); CO_2 evolution after re-wetting dry soil (Haney et al., 2001)] and field methods [eg., use of buried resin membrane strips to assess nutrient release rates (Qian and Schoenau, 2006)] have been proposed, but their use in nutrient management does not appear to be widespread.

Plant and soil biotechnology
Rapid advances are occurring in biotechnology of both the plant and in the soil. For example. DNA and gene manipulation to improve uptake of nutrients by manipulating the protein carriers in the roots (BBC today). In higher plants, two types of nitrate transporters, NRT1 and NRT2, have been identified. In Arabidopsis, there are 53 NRT1 genes and 7 NRT2 genes. Development of technologies are opening up this area and making it one of the more rapidly expanding frontiers of soil and plant science.

Fertiliser and nutrient technologies
The local scale conversion of small urea granules or ‘prills’ into larger pellets (‘supergranules’; 1-3 g granules) has been rolled out on a large scale in Bangladesh, where farmers apply the urea supergranules 5-7 cm below the soil surface by hand (or with a newly developed mechanical applicator) between rice seedling. This ‘fertiliser deep placement’ approach increases incremental yield by 15-18 percent per ha over surface applied urea using approximately one-third less N (78 kg N/ha vs. 118 kg/ha). Recent results using fertiliser deep placement of NPK briquettes has produced an additional 3-5 percent increase in incremental yield. This technology is estimated to reduce ammonia and other N losses substantially, significantly increasing nitrogen use efficiency (Savant and Stangel, 1990; Sutton et al 2013). Use of supergranules has the big advantage that a one-time application after rice transplanting is sufficient, whereas conventional surface

application of urea requires two or three split applications that can still result in significant N loss through ammonia volatilisation.

The use of slow- or controlled-release fertilizers (CRFs) provides another means to improve N management. Two important groups of fertilisers are classified as CRFs. One group is formed by condensation products of urea and urea aldehydes (e.g., urea formaldehyde). The second group comprises coated or encapsulated fertilisers, such as S-coated urea (SCU) or polymer-coated urea (SCU). Despite their potential to improve N use efficiency, use of slow- and controlled-release fertilisers is low in commercial agriculture because of their cost compared to conventional fertilisers (price of CRF can be 2.5 to 10 times that of conventional soluble N sources). As a result, use of CRFs is mostly confined to niche markets (nurseries, turfgrass, gardening). It has been estimated that CRFs make up only 8-10% of the fertiliser used in Europe, 1% in the USA, and 0.25% in the world as a whole. Useful information of CRFs can be found in recent review papers (Shaviv, 2001; Chien et al., 2009).

Application of microbial inoculants to the soil may enhance the uptake of nutrients by plants and increase the efficiency of mineral fertilisers and manures (Schoebitz et al. 2013).). Different encapsulation methods are available to cover and protect the microorganisms (e.g., sodium alginate is one of the most used products for bioencapsulation). Each encapsulation technique has advantages and drawbacks and the selection of a suitable method appears to depend on factors such as bacteria strain and cost.

Minimisation of Environmental Impacts

This is another outcome that goes hand in hand with increased production and the concept of sustainable intensification. A wide range of approaches to nutrient management science are reported. The following are taken directly from UK “Mitigation Guide – Users Guide” (Newell Price et al., 2011) and many will be very relevant to New Zealand.

- Use plants with improved nitrogen use efficiency
- Use a fertiliser recommendation system
- Integrate fertiliser and manure nutrient supply
- Do not apply manufactured fertiliser to high-risk areas
- Do not apply manufactured fertiliser at any time to field areas where there are direct flow paths to watercourses. For example, areas with a dense network of open drains, wet depressions (flushes) draining to a nearby watercourse, or areas close to road culverts/ditches.
- Avoid spreading manufactured fertiliser to fields at high-risk times
- Do not spread manufactured fertiliser at times when there is a high-risk of surface runoff or rapid movement to field drains i.e. when soils are ‘wet’.
- Do not spread N fertiliser when there is little or no crop uptake and there is a high-risk of NO_3 leaching loss (i.e., late autumn-winter); unless there is a specific crop requirement during this period.
- Use manufactured fertiliser placement technologies
- Place nutrients close to germinating or established crops to increase fertiliser N and/or P recovery (Placement of nutrients close to plant seeds and roots increases nutrient uptake efficiency
- Use nitrification inhibitors

- Incorporate a urease inhibitor with urea fertiliser
- Reduce nutrient losses through *site-specific* mitigation measures, including erosion control measures, cover crops, tillage management, best practices for fertiliser and manure applications, and buffer strips.

SUMMARY AND RELEVANCE TO NEW ZEALAND

Globally, demand for food will increase and this will ensure continued markets and opportunities for New Zealand Agriculture. Risks to food and fibre production will increase as a result of climate change, and it is likely that fertiliser costs will continue to rise. Concerns about the sustainability of agriculture and forestry systems will lead to more demand for green certification of products, and reduction or mitigation of environmental impacts. International research focus is on increased nutrient use efficiency, enhanced production and lower environmental footprints. These global trends are all directly relevant to NZ and will require a response. There do not appear to be any major science areas that we are not aware of though the emerging ‘biological and biotechnology area’ is one we should take close note of. Reviewing national NMS activities should be evaluated within the frame of these key global themes, improving best management practice, nutrient use efficiency, and technology developments leading to the overall outcome of sustainable intensification (increased productivity, reduced environmental footprint).

NATIONAL TRENDS IN NUTRIENT MANAGEMENT SCIENCE

REVIEW METHODS

The New Zealand literature was reviewed – both peer reviewed scientific and the grey literature such as technical reports. The review was segmented at a number of levels to cover the primary sector crops and New Zealand's environment using the following matrix:

- Nutrients (N, P, other where appropriate)
- Nutrient sources (e.g. fertilisers, effluent, legumes)
- Processes/Impacts/Interactions, (things that affect ability to give good management advice – e.g. leaching, soil microbial processes)
- Spatial Environmental Framework (soil orders, geographic regions)
- Outcomes
  - Productivity
  - Environmental Impacts
- Sector specific issues (arable, dairy, forestry, horticulture, pastoral)

The study reviewed literature published between 1998 and 2013. A literature search was done on the key words Nutrient Management Science, New Zealand, and Nitrogen, Phosphorus, and Potassium using a number of online bibliographic systems – Scopia, CABI, Web of Science. Literature retrieved from these searches was a mix of white (reviewed scientific papers) and grey (generally technical reports). Additional requests were made to the Fertiliser Association for any relevant literature, and MPI's database searched for relevant material. EndNote was used as the storage and analysis mechanism.

This first compilation was then further analysed for important key words related to soil processes, individual primary sectors, and nutrient sources to allow us to develop an overview of the relative activity in each of the areas, and for the science teams to sub-divide their analytical efforts into manageable sized portions.

The compilation was analysed by the science team and any irrelevant articles deleted to generate a final bibliography for the review. The bibliography was compiled as an EndNote library with key word sub-libraries that included citation and abstract. A citation only version of this library is appended (Appendix 2).

An analysis was then undertaken of the science advances within each segment and knowledge frontiers and gaps identified.

FINDINGS

Nutrient Management Science Literature meta-analysis

The analysis reported in this section aimed to develop a broad understanding of the balance of research effort undertaken on Nutrient Management Science in New Zealand between 1998 and 2013 and was based on the body of published papers and reports. The balance of research activity across the various keyword groupings is outlined in Figure 6. Detailed analysis of the literature itself is covered in following sections of this report.

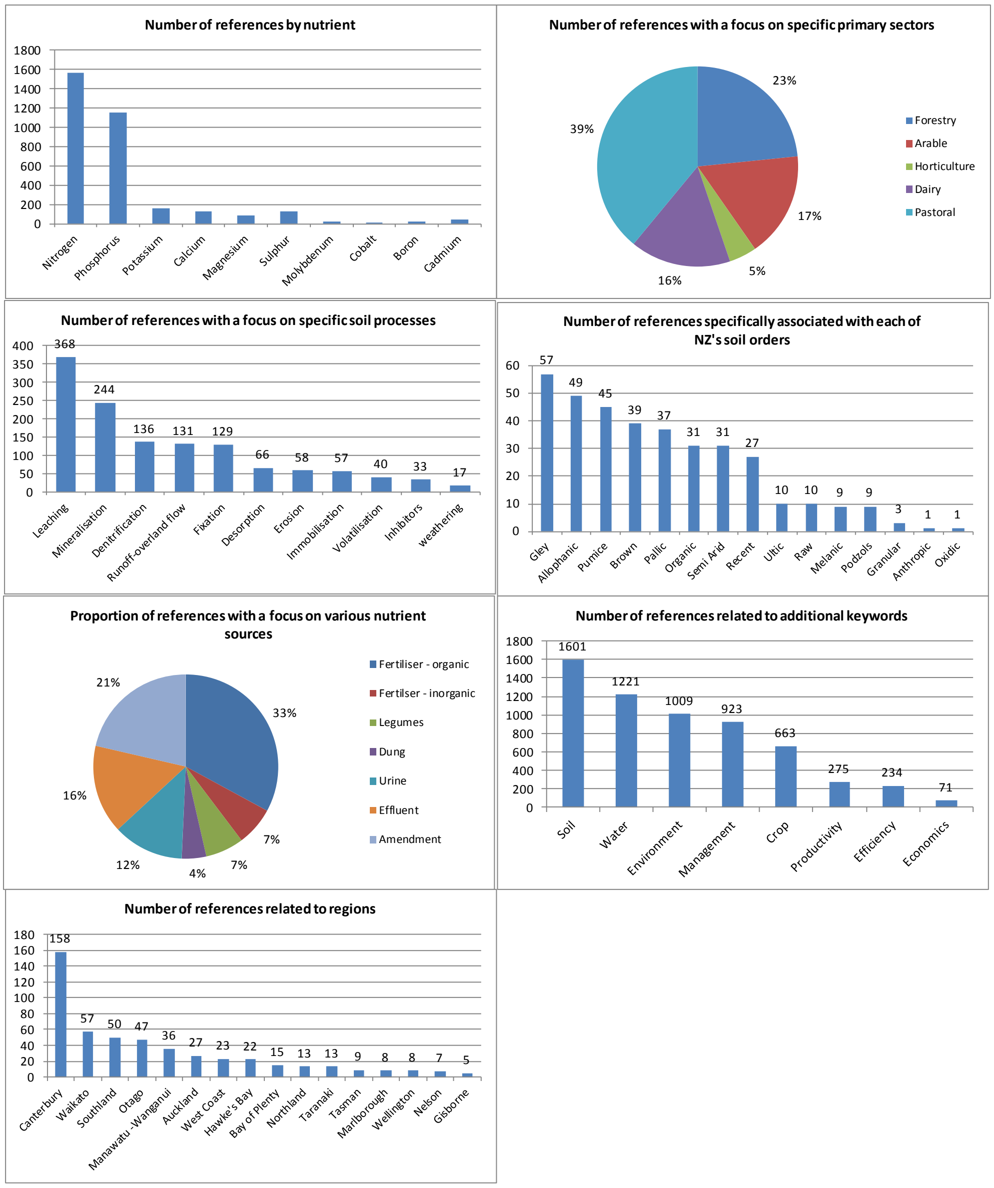


Figure 6. NMS Literature meta-analysis

The compilation of literature into the EndNote database identified 1915 articles in total from the search containing the full suite of keywords. The focus of the review was on Nitrogen and Phosphorus and in the database most mentions were made of Nitrogen (1567) and then Phosphorus (1148). Other elements are also important and frequency of reference is summarised here also. Generally, however they were mentioned in less than 10% of papers in the database. Effort varied across the five land uses analysed with the order of emphasis pastoral > arable > dairy > forestry > horticulture

Of the soil processes most work has been published on leaching followed by mineralisation, de-nitrification, and run-off/overland flow, these five processes contributing to 70% of the articles. Seven nutrient sources were identified, with the most published work on fertilisers (both organic and inorganic), making up 40% of

those articles where nutrient sources were identified. The grouping of Dung, Urine and Effluent contributed to 33% of references – indicating the importance of the animal in New Zealand's primary sector systems. While soil was referenced in around 70% of all the literature, refining this analysis to relate research to either specific soil orders or regions was not very successful suggesting that if research result application is to be effective more emphasis on this area may be warranted.
A search of keywords in addition to the main suite indicated overall focus has been on the soil, environment, and management. Efficiency, a major international topic was only mentioned in a minor way, productivity slightly more, but economics hardly at all. This latter point suggests there may well be a gap between predominantly biophysical research and the business side of Agriculture, Forestry and Horticulture.

BACKGROUND TO NUTRIENTS AND NUTRIENT CYCLES

This review focuses on two major nutrient elements: nitrogen (N) and phosphorus (P). Nitrogen is an essential element for all organisms, occurring primarily in the form of amino acids (and thus proteins) and nucleic acids (DNA and RNA). Phosphorus is also an essential nutrient for plants and animals. The primary biological importance of phosphates is as a component of nucleotides, which serve as energy storage within cells (ATP) or when linked together, form the nucleic acids DNA and RNA.

Nitrogen cycle

The nitrogen cycle includes the major pools of N and the processes by which N is transformed into its various chemical forms (Figure 7). The transformations N are carried out by both biological and physical processes. The most important transformation processes in the N cycle include fixation, ammonification (mineralisation), nitrification, and denitrification. The majority of Earth's atmosphere (78%) is nitrogen, making it the largest pool of nitrogen. However, atmospheric nitrogen has limited availability for biological use, leading to a scarcity of usable nitrogen in many types of ecosystems. The nitrogen cycle is of particular interest to the agricultural and environmental sectors because nitrogen availability can affect the rate of key ecosystem processes, including primary production, decomposition and transport across ecosystem boundaries.

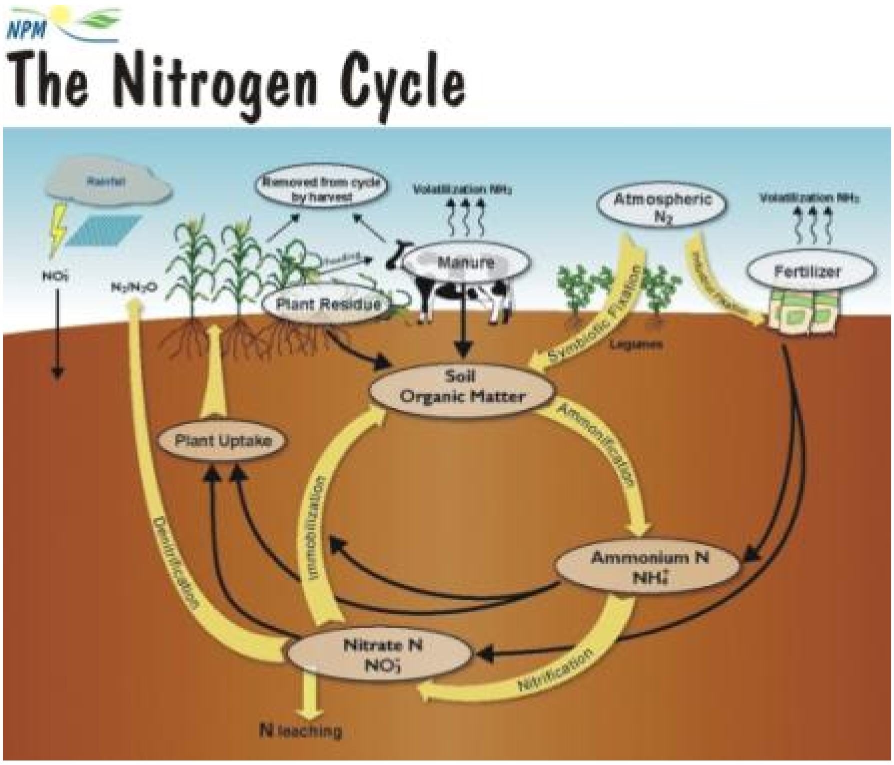


Figure 7. The Nitrogen Cycle (Source: http://fyi.uwex.edu/discoveryfarms/2010/).

Nitrogen is present in the environment in a wide variety of chemical forms including ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), nitrous oxide (N_2O), nitric oxide (NO), di-nitrogen gas (N_2) and a range of different organic N compounds. Organic nitrogen may be in the form of a living organism, soil organic matter (humus) or in various intermediate products of organic matter decomposition. Most of the processes that transform N from one form to another are carried out by microbes, either in their effort to harvest energy or to accumulate nitrogen in a form needed for their growth. Figure 7 above shows the sources and major pools of N in the soil-plant-atmosphere system and the transformation processes that together make up the nitrogen cycle.

The N transformation and transport processes that are discussed in this review include: fixation, mineralisation, assimilation, nitrification, denitrification, and leaching.

Assimilation is the process by which plants take up nitrogen from the soil, by absorption of N through their roots in the form of either nitrate ions or ammonium ions and the eventual incorporation into amino acids, nucleic acids, and chlorophyll. All of the N used by animals to grow and reproduce can be traced back to the eating of plants at some stage in the food chain. While many heterotrophic organisms (e.g. animals, fungi) obtain nitrogen by ingestion of N-containing organic compounds, other heterotrophs (including many bacteria) are able to utilize inorganic compounds, such as ammonium as sole N sources. The uptake of both organic and inorganic forms of N by soil organisms (especially microorganisms) is often referred to as immobilisation.

The waste products of plant and animals and their remains when they die are converted by bacteria and some fungi from their original organic forms to ammonium (NH_4^+) through a process called **ammonification** or **mineralisation**. The conversion of ammonium (NH_4^+) to nitrate (NO_3^-) is carried out primarily by soil-borne bacteria in process known as **nitrification**. In the first stage of nitrification, ammonium (NH_4^+) is oxidised by bacteria such as the *Nitrosomonas* species, which converts ammonia to nitrites (NO_2^-). Other bacterial species, such as the *Nitrobacter*, are responsible for the oxidation of the nitrites into nitrates (NO_3^-). The rapid conversion of ammonia to nitrate is important because accumulation of nitrites can be toxic to plant life. Owing to the high solubility of nitrate, and because soils generally have a low capacity to retain anions, nitrates can be readily transported from the top soil, through the vadose zone to enter groundwater. This transport process is typically referred to as **nitrate leaching**.

Denitrification is the reduction of nitrates to form the greenhouse gas, nitrous oxide (N_2O) and further to form inert di-nitrogen gas (N_2). This process is performed by bacterial species such as *Pseudomonas* and *Clostridium* under anaerobic conditions. They use the nitrate as an electron acceptor in the place of oxygen during respiration. These facultative anaerobic bacteria can also live in aerobic conditions.

Phosphorus cycle

Phosphorus normally occurs in nature as part of a phosphate ion $(PO_4)^{3-}$, the most common form being orthophosphate. On land most P is found in rocks and minerals; the weathering of these materials release P in a soluble form where can be taken up by plants, and converted into organic compounds. Animals obtain their P from plants, directly or indirectly through the food chain. During the decay of plants and animals, P is returned to the soil where a large part of it is converted into insoluble compounds. Runoff from soil can carry a small quantities of P (mostly attached to soil particles) into waterways and out to ocean.

The phosphorus cycle, the major pools of phosphorus, and the processes by which P is transformed are outlined below (Figure 8).

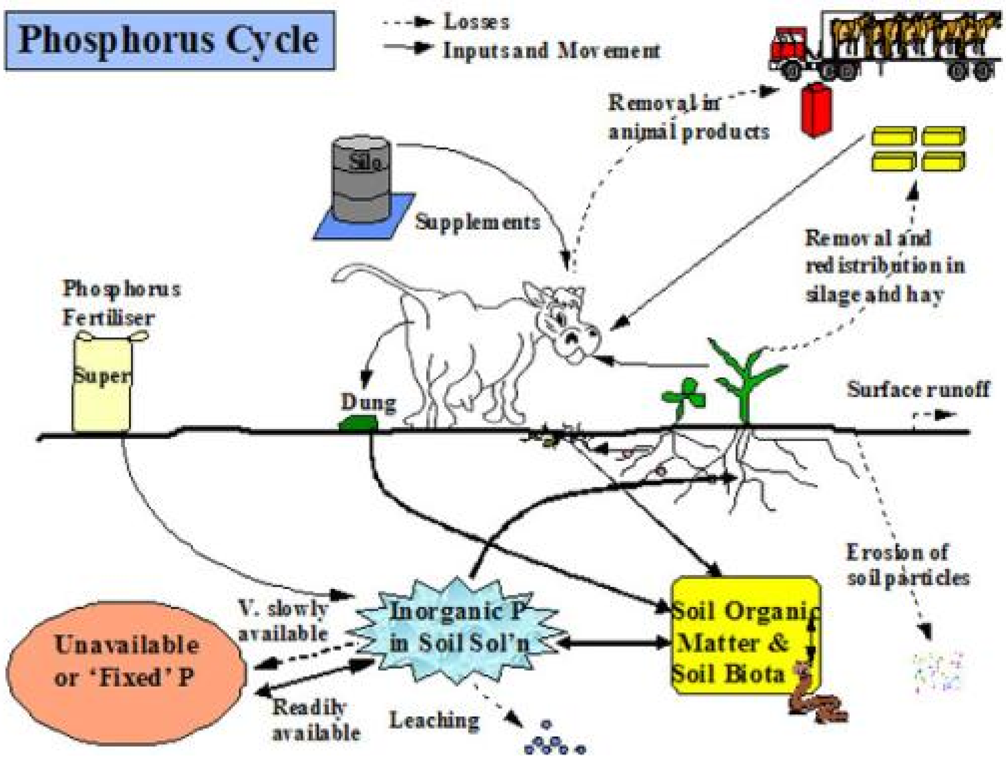


Figure 8: Phosphorus Cycle

Organic P (Po) usually represents between 20 and 80% of the P in soils. Transformations of P via the immobilisation-mineralisation process play an important role in the cycling and bio-availability of P in soils. Phosphate released by mineralisation of Po can make an important contribution (albeit a poorly defined contribution) to the supply of plant-available P. Conversely, some inorganic P applied in fertiliser may be incorporated into Po forms that accumulate in soil organic matter. Although considerable progress has been made in identifying specific Po compounds using nuclear magnetic resonance, much remains to be understood about the nature and dynamics of Po. Animal excreta (dung) and plant residues represent the major inputs of Po to soil.

Inorganic P in soils can be present in discrete calcium phosphate minerals or in adsorbed form associated with surfaces of silicate and, particularly, oxide (Fe, Al) minerals. In soils that have not been extensively weathered, P mineralogy is dominated by sparingly soluble apatites [$Ca_{10}X(PO_4)_6$ where X can be OH^-, Cl^- or CO_3^{2-}] and other more soluble calcium phosphates [e.g., $Ca_8H(PO_4)_6.H_2O$] . Release of P by weathering of primary Ca minerals can be very slow. Limited data for NZ suggest P release rates by mineral weathering of about 0.2 to 3 kg/ha per year. The total input of P by weathering in NZ has been estimated at 40 Gt/yr (vs ~210 Gt/yr in fertiliser) (Parfitt et al. 2008).

There is general consensus that the availability of P to plants is regulated mainly by the adsorption-desorption process. Phosphate is adsorbed to soil minerals with a continuum of bonding energies, such that the more strongly adsorbed the P is, the less available it is for uptake by plants. Thus phosphate in soil can be categorised into "pools" or 'fractions" in terms of its plant availability (or extractability using chemical reagents). One proposed scheme (Syers et al., 2008) divides soil phosphate into four pools, including P in soil solution (immediately available), weakly adsorbed P (readily available) and forms of P with low and very low availability (Figure 9). Tests for plant-available P (eg Olsen bicarbonate extraction) are intended to extract the immediately- and readily-available P.

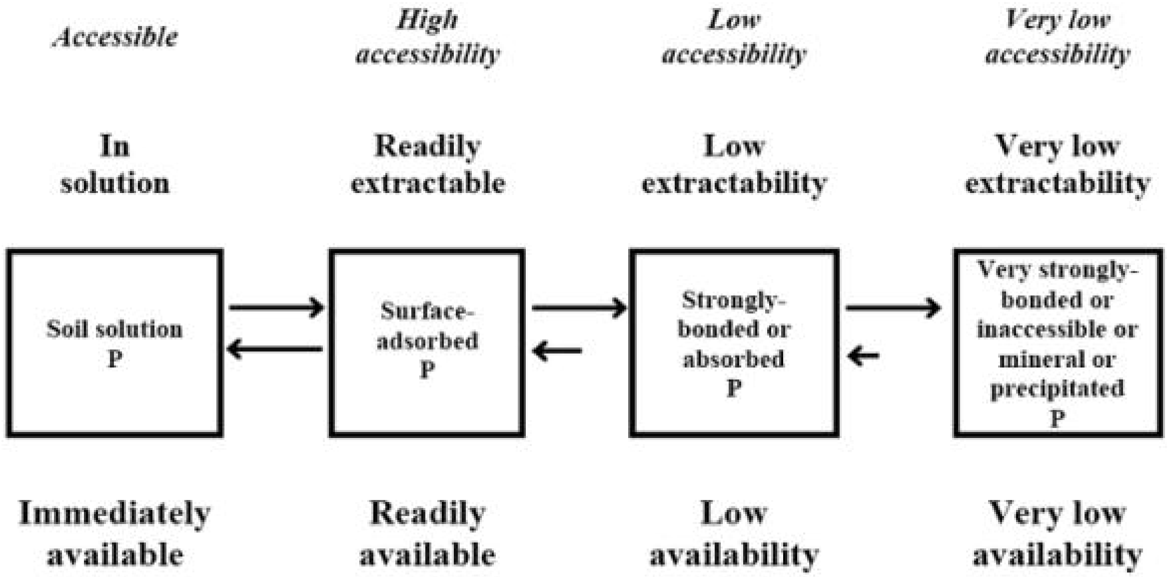


Figure 9. Phosphorus pools

Apart from plant off-take of P, P can be lost from soil by leaching, in surface runoff or by soil erosion. Because the concentration of P in soil solution is normally very low (<0.1 mg/L), leaching losses are generally small except possibly where there is preferential leaching immediately after application of effluent or fertiliser. Surface runoff, which can have a substantial particulate P component, can be an important loss pathway for P in situations where overland flow is significant. Although the total quantity of P lost in runoff may be relatively small (average of 0.2 kg/ha per year; Parfitt et al., 2008), it can have a major impact on the quality and ecology of surface water.

REVIEW FINDINGS

Soil processes

Nitrogen mineralisation

Soil N mineralisation is the process that involves the breakdown of organic forms of N and the release of mineral N (i.e. NH_4^+ and NO_3^-). Net N mineralisation is the most common approach to measuring N mineralisation and is based on the accumulation of mineral N (NH_4^+ and NO_3^-) in soil over a fixed period of time where the transformations and losses of mineral N are not specifically accounted for. Consequently, net N mineralisation excludes any mineral N that is taken up by plants or immobilized by soil microbes, any gaseous emissions of N (e.g. N_2O, N_2) that result from nitrification or denitrification and any NO_3^- leached from the soil over the measurement period. Gross N mineralisation is the total amount of N mineralised under defined conditions over a fixed period of time, where all of N mineralised is accounted for including any of the transformations or losses described above. It is undoubtedly the best measure of the mineral N supplied by

SOM decomposition as a source of N for N_2O production, but it requires the use of more complex and expensive analytical techniques (e.g. ^{15}N isotope dilution).

Laboratory-based measurements of net or gross N mineralisation are commonly made under conditions of constant soil temperature and moisture. These conditions are often selected to represent "optimal" temperature and moisture (though they can vary widely from one study to the next). Field-based measurements of net N mineralisation can provide a better measure of the actual rates of mineralisation where they include natural variations in temperature and soil moisture, but these same variations may contribute to higher or lower losses of mineralised N (as N_2O emissions or NO_3^- leached), and therefore under or over-estimate the actual rates of SOM mineralisation. Another important consideration in measuring N mineralisation, particularly for pastoral soils, is soil disturbance. Standard laboratory protocols (developed originally for cropping soils) call for the sieving of soils to remove roots and crop residues prior to incubating the soil under defined conditions to measure the N released. This form of soil preparation is likely to result in an overestimate of the actual N mineralisation potential of pastoral soils owing to greater aeration of the soil and increased exposure of the organic matter to microbial attack.

Predicting the supply of mineral N from the mineralisation of soil organic matter over a growing season depends on being able to: 1) quantify the size of the potentially mineralisable pool of N and 2) understanding the effects of soil physical and environmental conditions on actual release of N from mineralisation over that period.

Knowledge frontier and gaps; N mineralisation

- *Net N mineralisation*: Although soil type and management history can provide a rough guide to a paddock's N mineralisation potential, the need for a more reliable and robust mineralisation predictor has been on-going driver for soil N research in NZ and internationally. This remains a significant limitation to accurate forecasting of fertiliser N requirements of crops and should be a high priority for future research.
- *Mineralisable N tests*: the existing commercially available test for potentially mineralisable N, which is based on an anaerobic incubation carried out at high temperature (40^{o}C), has not been well calibrated for NZ conditions and this limits its utility in fertiliser N decision making. Research suggests that an aerobic incubation assay is superior to the anaerobic test, but it has some practical and operational disadvantages (e.g., longer incubation period) that make it unattractive for routine soil testing. The development of a more accurate, yet practical test should be a high priority for future research.

Nitrification

Nitrification is a microbial process by which reduced nitrogen compounds (primarily ammonia) are sequentially oxidized to nitrite and nitrate. The nitrification process is primarily accomplished by two groups of autotrophic nitrifying bacteria that can build organic molecules using energy obtained from inorganic sources, in this case ammonia or nitrite. In the first step of nitrification, ammonia-oxidizing bacteria oxidize ammonia to nitrite according to equation (1):

(1) $NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$

Nitrosomonas is the best known genus of microorganisms associated with this step, although other genera, including *Nitrosococcus,* and *Nitrosospira* also contribute*.* Some subgenera, *Nitrosolobus* and *Nitrosovibrio,* can also autotrophically oxidize ammonia.

In the second step of the process, nitrite-oxidizing bacteria oxidize nitrite to nitrate according to equation (2).

(2) $NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$

Nitrobacter is the most commonly identified genus associated with this second step, although other genera, including *Nitrospina*, *Nitrococcus*, and *Nitrospira* can also autotrophically oxidize nitrite. Various groups of heterotrophic bacteria and fungi can also carry out nitrification, although at a slower rate than autotrophic organisms.

Denitrification

Denitrification is a microbially mediated process that results in the reduction of nitrate to form molecular nitrogen (N_2) and a series of intermediate gaseous nitrogen oxide products.

It is a respiratory process that reduces oxidized forms of nitrogen in response to the oxidation of an electron donor such as organic matter. The preferred nitrogen electron acceptors are nitrate (NO_3^-), nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) resulting in the production of dinitrogen (N_2) as the final product. The process of denitrification is carried out primarily by heterotrophic bacteria (e.g. *Paracoccus denitrificans* and various pseudomonads), although some autotrophic denitrifiers (e.g., *Thiobacillus denitrificans*) have also been identified. In most instances several species of bacteria are involved in the complete reduction of nitrate to molecular nitrogen, and more than one enzymatic pathway has been identified in the reduction process. The genes and organisms involved in reduction of nitrite and nitrous oxide have also been identified.

Knowledge frontier and gaps; Nitrification and denitrification

- *Interactions of soil physical, chemical and biological properties*: The biological and chemical processes that result in denitrification are relatively well known. Although the critical factors that affect rates of denitrification are known (oxygen, carbon and nitrogen oxide availability) the interplay between these various factors is not fully understood at the field or cellular level. A much greater understanding of how soil physical and biochemical factors interact to affect denitrification rates and the specific end products is needed.
- *Metrics for mitigating losses*: There is a need to develop relatively simple metrics that can be used to predict the ratio of N_2O to N_2 and the absolute levels of N_2O emissions from soils under different soil physical (e.g. pore size distribution, water-filled porosity, diffusivity) and chemical (e.g. nitrate availability, organic matter content and quality, pH etc) conditions. This could lead to improved recommendations for application on-farm.
- *Models and decision support tools*: Understanding the interactions between soil physical and chemical properties is important to developing models and decision support tools that assist farmers (often through farm consultants)

to manage the risks of gaseous emissions and thereby, reduce the environmental impacts of nutrient intensive systems.

Nitrogen leaching

Leaching refers to the transport of water-soluble nutrients down the soil profile, usually due to excess drainage from rain or irrigation. Soil structure, crop planting, type and application rates of fertilizers, and other factors have been shown to be important to avoiding excessive nutrient loss. Leaching is an environmental concern when it contributes to groundwater contamination. As water from rain, flooding, or other sources seeps into the ground, it can dissolve chemicals and carry them into underground aquifers and surface water bodies .

Nitrate (NO_3^-) is one of the most important and well know forms of nitrogen that is leached from agricultural production systems and is blamed for the rise in NO_3^- concentrations in ground- and surface-waters around the world. The processes that regulate the formation of nitrate (mineralisation and nitrification) and affect the transport of nitrate down the soil profile are relatively well known. However, there are important gaps in our understanding of soil physical properties that affect the infiltration and drainage of water from soils that have important implications of nitrate leaching. Some of the management practices that have been identified to mitigate NO_3^- leaching from agricultural production systems are discussed in the sector based analyses outlined below. In addition to nitrate, there has been recent interest in quantify the leaching of dissolved organic N (DON) and understanding the factors that affect its contributions to N losses from agricultural production systems.

Knowledge frontier and gaps: Nitrogen leaching

- *Interactions of drainage and nitrate leaching*: Research is needed to improve our understanding of soil physical properties that affect the amount and form of water drained from soils and their effects on nitrate leaching losses.
- *Leaching of dissolved organic N*: Better quantification of the DON leaching losses is needed across a range of production sectors. Understanding the sources and supply of the DON that is at risk of leaching and the contributions of leached DON to nitrate accumulation in ground- and surface-waters and to gaseous emission of N is also needed.
- *Improved models of drainage and leaching losses*: Better knowledge of soil physical controls on drainage and leaching is important to improving model prediction of losses. These improvements are critical to improving fertiliser N forecasting and predicting the effects of land use and management change on losses from different production systems. These tools are also important in identify management to mitigate losses across different production sectors.

Sector based analysis of nutrient management science: Pastoral

Nutrient sources: nitrogen

N fertiliser

Statistics show that nitrogen fertiliser use has increased in the last 15 years. This is mainly driven by the dairy industry and urea is the main source of N. Historically, there has been a huge research effort in N fertiliser response trials. However, the majority of this work was completed in the 80s and falls outside the scope of this report. More latterly, most of the data to that date have been consolidated into a single database with funding from the Fertiliser Association of New Zealand (databases for other nutrients have also been assembled).

Scientific advances in the period 1998 to 2013: Pastoral, N fertiliser

Research tends to separate into 2 scales: farm-level (productivity, profitability, and footprint) and individual application level (right place, right time, right amount). These two aspects could also be considered as strategic and tactical aspects of N fertiliser management. Furthermore, the effects of N fertiliser on N loss processes could be considered as 'direct' (i.e. loss from the applied product) or 'indirect' (loss from the excreta arising from the extra forage produced by N application). Research in dairy and dry stock sectors has focussed on:

- *Managing N fertiliser at the farm level*: modelling and measurements to understand the overall implications on productivity, profitability and footprint of introducing or increasing N fertiliser use in a farm system. Research has been undertaken on both dairy and upland farm systems. Includes:
    - Strategic management of N fertiliser in the farm system
    - Understanding interactions of fertiliser, feed and legume N supply
    - Implications for grazing management
- *Pasture N response*: this is limited to experiments in specific locations to fill gaps in knowledge. Predominantly now funded and/or undertaken by industry. Historic data have been used to provide generalised recommendations (e.g. DairyNZ, 2008).
- *Soil processes*: limited research on detailed understanding of soil dynamics of N fertiliser.
- *Losses*: some research on quantifying and addressing N_2O, NH_3 and NO_3 losses from fertiliser applications
- *Technologies*: application, process inhibitors and sensors for pasture yield/nutrient content is discussed elsewhere.

Knowledge frontier and gaps: Pastoral, N fertiliser

Nitrogen fertiliser increases productivity by producing more forage which needs to be converted to product; this is well understood. The subtlety is that an efficient pastoral system is about producing forage of the right quality and at the right time. If this balance is lost quality and yield can be lost in the longer-term: this is well understood.

Inefficiencies lay in: effective conversion of N fertiliser to forage; impacts on feed N concentration; grazing and conservation strategies to efficiently utilise the extra forage; animal feed conversion efficiency; and proportion of consumed N that is excreted. Again, all of these principles are understood and research is on-going in all areas.

Improved fertiliser N response at the individual application level: pastoral

The industry is committed to improving the kg dry matter produced per unit N applied at each application. Myriad factors affect pasture N response. Historic trials have provided an understanding of this response and its variation but knowledge gaps include:

- *Quantifying soil N supply:* a better quantitative understanding of release of mineral N from soil organic matter.
- *Modelling of N fertiliser response*: adaptation of process-based models to support the development of N fertiliser recommendations may be a cost-effective way of extending coverage beyond locations and conditions of fertiliser response trials.
- *Non ryegrass/clover pastures*: more work required on other pasture types, particularly as the use of diverse pastures is being advocated as a strategy for improving N use efficiency; including impact of N fertiliser on persistence of the non-ryegrass/clover pasture species in a sward.
- *Decreasing losses*: improve efficiency by decreasing gaseous and leaching losses. Work on urease inhibitors is mature. Little work on leaching risk of N applied in winter or on the autumn/spring shoulders, or interactions with irrigation. Work with fertiliser additives/coatings is on-going.
- *Fate and behaviour of fertiliser N in soils*: underpinning science, to support all of the above, and also to define the interaction of N with C and longer term consequences of N fertiliser use for soil C status.
- *Fertiliser application*: see 'technologies'

Strategic management of fertiliser N: pastoral

A significant portion of research has focused on understanding management and impacts of N fertiliser at the strategic level, e.g., how to manage N in relation to other feed sources (including N and forage from atmospheric fixation); how to manage grazing; implications for N losses (primarily through the urine patch); and decreasing these 'indirect' losses. The latter is about minimising the impact of the increased excreta deposition due to increased stocking rate and forage intake. Key to improved nitrogen use efficiency at the farm level is clarifying periods of highest risk of N use (protecting against direct or indirect losses) and defining best when to use N in a systems context.

Current research is focusing on systems that are now looking to operate at lower N inputs whilst maintaining the same level of productivity (for example the joint industry-government funded Pastoral 21 research programme); this has highlighted gaps in our knowledge around systems response and best fertiliser N strategies.

N fixation by legumes

Nitrogen fixation by legumes, predominantly via clover/grass pastures, has long been a fundamental component of NZ pastoral production systems. Management challenges around legume use include seasonality of growth, pest risk in some regions, and persistence in systems that also use fertiliser N.

Scientific advances in the period 1998 to 2013: pastoral, legumes

Given the importance of N fixation to NZ production systems, we assume that a significant amount of research has historically been undertaken but falls outside the 15 year timeframe (e.g. Brock et al. 1989). Research can be categorised into gaining strategic understanding at the farm level, legume agronomy or tactical management of legumes, and some detailed understanding of N fixation, in both dairy and dry stock sectors.

- *Managing legumes at the farm level*: research has focused on:
    - Productivity and profitability of systems - managing the system to optimise return from legumes – e.g. grazing management, interaction with N fertiliser applications
    - Comparative N losses – from legume and legume/fertiliser N farm systems, both through measurement ('farmlets') and modelling. Emphasis mainly on N leaching, though some investigations also into Greenhouse gases
- *Quantifying N fixation*: estimating dry matter and N yields and N_2 fixation from legumes; effects of management factors (e.g. pugging); some detailed research on the N fixation process
- *Agronomy*: Management of different legumes for yield and productivity
- *Interaction with other nutrients*: most notably basal P fertility but also response to a range of other nutrients
- *Interaction with N sources*: e.g. impacts of fertiliser, urine or effluent on N fixation and on productivity
- *Legume improvement*: developing different inoculants, developing and/or testing different legumes

Knowledge frontier and gaps: pastoral, legumes

Legumes are a good food source for ruminants and are also recognised as a valuable source of N for the farm system, but their optimal management to ensure consistent N fixation is a challenge. There is reasonable quantitative understanding of the contribution that N fixation can make in farm systems. There is also a good understanding of the need for good basal soil fertility to encourage persistence of legumes. However, a fundamental question that remains unanswered is whether legume-based systems are indeed more N efficient than fertiliser-based production systems.

Breeding for improved legume performance and developing improved rhizobia strains is on-going, but progress is slow; begging the question whether there are alternative approaches to accelerate progress.

Important areas of required scientific advancement are related to agronomic questions that will improve legume N fixation in the production system, such as:

- Managing pastures in spring to enhance clover production and N_2 fixation, and implications for animal productivity
- Optimising grass and clover varieties for N_2 fixation
- Establishment of legumes under the different methods of pasture renovation

Most hill country pastoral systems are totally reliant on biological N fixation and there is little if any work on improving clover survival and function in these environments.

Nutrient sources: phosphorus

Fertiliser

Phosphorus fertilisers are added to pastures to increase soil P levels to economic optimum levels for pasture production. The forms of P fertilisers on the market vary in their solubility, which affects plant uptake of P and risk of 'direct' loss in runoff. As with nitrogen there are also 'indirect' effects of P fertiliser on risk of P loss due to increased pasture production leading to increased stocking rates, increased returns in excreta, and the potential for increased treading damage and soil compaction.

Scientific advances in the period 1998 to 2013: pastoral, P fertiliser

- *Response and defining optimal requirements:* Research undertaken during the 1990s defined the production functions between pasture production and soil P, K and S. From this the optimal soil nutrient levels could be better defined, and dynamic P, K and S models developed. This in turn allowed the economic optimal nutrient levels to be defined, which is very relevant to NUE and environmental management.
- *Characterisation:* Super phosphate (super P) is the most soluble fertiliser commonly used and therefore the response to additions of super P will be the fastest, while responses to lower soluble forms of P, like reactive phosphate rock (RPR), will be slower, but last longer. The research farms at Winchmore (Canterbury), Whatawhata (Waikato) and Ballantrae (Hawke's Bay) have contributed to understanding the impacts of long-term applications of P fertilisers on sheep and beef country. These effects have been measured in terms of characterisation of soil P forms (organic and inorganic), plant availability, and P losses in overland and subsurface flow.
- *Associated heavy metals:* Research has shown the rate of heavy metal deposition from the atmosphere to generally be lower than rates measured in other countries, reflecting the general lack of high temperature industrial processes that are an important source of heavy metal aerosols in other regions. In pastoral agriculture, the major source of heavy metal contamination is P fertiliser. Cadmium (Cd) and fluorine (F) are the elements of greatest concern. Phosphorus fertilisers vary in their Cd contents with the greatest contamination found in sedimentary P deposits. Fluorine accumulation is mainly associated with single super P application.
- *Leaching:* There have been few studies into the loss of fertiliser P via leaching, but limited results have shown it not to be an issue. On a soil with low P retention (and therefore greatest risk of P loss), there was no difference in leachate P from a fertilised and unfertilised control.
- *Overland flow:* The greatest risk of P fertiliser loss comes in the period just following application (termed incidental loss). The length of time that the risk persists depends on the local conditions, and solubility of product. Lower, more sustained losses come from the indirect effect of P fertiliser through increased soil P levels which have been found to be proportional to P loss in overland flow.

- *Strategies:* As with other fertilisers, accurate placement/spreading and the timing of fertiliser application ensures a good response with minimal loss of nutrients. It is important to identify and avoid applying P on areas that already have elevated P inputs (e.g. nutrient rich areas such a stock camps), and plan application for times when rain is unlikely (e.g. summer).
- *Technologies:* Some research has been done into adding coatings (e.g. sulphur) to soluble P fertilisers to reduce the risk of P loss in runoff. Another approach trialled in Otago has been to separate pasture/clover swards in to individual components on the farm; i.e. planting ryegrass in areas with higher risk of P runoff and clover in the lower risk areas. The ryegrass component of the pasture requires lower soil P status and so planting ‘critical source areas’ (CSAs) with ryegrass appears to lessen the risk of P runoff.

Knowledge frontier and gaps: pastoral, P fertiliser

The amount of fertiliser P lost directly (e.g. in runoff) is a small proportion of that applied. 70-95% of applied P fertiliser is tied up by physical and biological processes in the soil , but the efficiency of use of P added in fertilizers is often high (up to 90%) when account is taken of uptake of this residual P over an adequate time scale. Nevertheless, papers recommend that options for accelerating recovery of residual P should be explored. For example, there is potential of utilising P-solubilising bacteria to enhance the plant-availability of P in soils, and selecting plants with greater P use efficiency will ensure the greatest value from applied P. There is also an excess of P from sources like factory farms (e.g. poultry, piggeries) that can be recycled, in some locales. Work has been done reducing point source P losses from domestic and factory wastewaters, but less work has been done in closing the P cycle by bringing these nutrients back to the farm.

Grazing

Here, we focus on the physical disruption of soil associated with grazing rather than dung as a source of P. There has been one long term study on the effects of beef cattle grazing. The remaining work has focused on the short term impact of treading of sheep, cattle and deer as well as the contribution of P in dung from these animals.

Scientific advances in the period 1998 to 2013: pastoral, grazing

- *Treading*: Treading contributes to P loss in two different ways, it contributes directly to P loss via dislodgement of soil and dung particles which may be caught up in overland flow and lost (erosion). Treading also indirectly contributes to overland flow losses of P though compaction. High treading intensity, or stocking rates, has been found to reduce the infiltration capacity of pasture and cropped soils, increasing the volumes of overland flow.
- *Behaviour:* The management and behaviour of animals has created other small point source areas within the paddock, such as around watering troughs, and outside paddocks in dairy laneways used for moving stock, which receive intense inputs in the form of dung and treading. Laneways can also be especially problematic in that often they can have drains/side ditches with direct outlets into waterways.

- *Stream access*: Stock access (sheep, beef, dairy and deer) to waterways increases P losses through the physical disturbance of banks and sediment, and the direct deposition of excrement. It has been found that the direct access of stock to streams results in greater loss of P than poor winter grazing management within the paddock.
- *Forage crops:* Many farmers (sheep, beef, dairy and deer) use forage crops in the winter as a source of alternative feed; therefore, there has been a number of studies looking at the difference in runoff of P from grazed forage crops compared with pasture. Most of these have been in Southland on heavy pallic soils - soils developed on loess that are subject to drying and cracking but subsurface clays that expand in winter leading to soil compaction.
- *Strategies:* Strategies to reduce P losses from grazing aim to reduce the time spent grazing when the potential for P loss are high (winter), and/or the use of sacrifice paddocks where the negative effects of grazing will be to a limited area. Fencing off waterways will stop the direct access of stock to streams. Also, grazing source areas last has been found to significantly reduce loads of P and sediment from winter forage crop areas.
- *Technologies*: Standoff pads, feed pads and herd homes have been developed and tested to reduce the amount of time that animals are on the paddock in wet weather and concentrate dung inputs to one area that can later be distributed across the farm. The application of aluminium sulphate (Alum) has been used to target point sources of P in dairy catchments. (The Al in alum forms aluminium phosphate which is largely insoluble and unavailable for plant/algal growth).

Knowledge frontier and gaps: pastoral, grazing

The development of efficient technologies to filter P (physical and biological) from ditches draining laneways and other point source areas of P loss on farms needs more attention. Forage cropping has become an important part of many pastoral farming systems. However, there has been no work done on the long term effects of repeated winter forage cropping and grazing.

Soil

Soil as a source of P is entwined with the other sources of P (effluent, dung and fertiliser), because adding these sources to the soil increases the levels of available P in the soil (usually measured in New Zealand as Olsen P, which is proven as appropriate for NZ soils). Soils themselves can act as a source in two ways. The first is by desorption of soluble P to the soil solution and overland or subsurface flow. The second is by erosion of soil particles due to raindrop impact or grazing or other soil disturbance. The risk of P loss from soils is determined by the P sorption/retention of the soil type and presence of Al and Fe oxides that can adsorb P.

Scientific advances in the period 1998 to 2013: pastoral, soil P

- *Characterisation*: The plant availability of P in different soils across New Zealand was found to depend both on the current and historical land use, and time since development. Physical characteristics of the soil, such as aggregate size and the proportion of light fraction organic matter have been found to influence soil P losses. Also, other physical characteristics, like soil infiltration rates and levels of soil compaction, affect the transport pathways of water and nutrients.

- *Overland flow:* Phosphorus enrichment levels, measured as Olsen P or a combination of Olsen P, P sorption index and %P, have been useful in estimating the loss of P in overland and subsurface flow. Studies using a range of NZ grassland soils have identified Olsen P change points, or thresholds, above which the potential loss of P in overland flow is significantly increased. These change points are often above the target Olsen P levels for optimum pasture production. Recent work has also investigated how physical factors, like slope and groundcover, are important for protecting the soil surface and for arresting overland flow.
- *Leaching:* leaching has been given less attention than overland flow as a pathway for P loss from soil sources, although it has been found to be a significant pathway in some studies. As with overland flow, the levels of available phosphorus and the sorption capacity of the sub soil will affect the amount of loss in subsurface flow. Additionally, seasonal changes in the fractions of P leached, and the effects of irrigation, have also been documented.
- *Strategies:* All data points to keeping Olsen P levels at or below the agronomic optimum (or target soil test values). This is the most profitable strategy in terms of pasture production, fertiliser costs, and keeping soil P losses to a minimum. If Olsen P levels are above optimum, withholding or reducing P fertiliser inputs below maintenance levels can run down Olsen P to optimum levels over time. However, this can have the negative long-term impacts on production and an increase in undesirable pasture species. The use of nutrient budgeting (e.g. using OVERSEER) will also help to prevent the accumulation of P in soil.
- *Technologies:* Cultivation has been used to redistribute the soil P more evenly in the soil profile and reduce P accumulation the surface layer. Also the use of cover crops and no-till methods has been found to protect the soil surface and .increase infiltration. Methods to increase infiltration rates and promote more uniform contact with soil matrix will lower the risk of runoff, and use the filtering properties of soil more efficiently. The use of constructed wetlands, sedimentation ponds, and buffer strips (edge or within field) have been examined for reducing nutrients loads from both diffuse and point sources on farms. In addition, the construction of detainment bunds, that slow the flow of ephemeral streams, have shown promise by arresting storm flow and allowing water to infiltrate and deposit sediments which can then be taken up by growing pasture.

Knowledge frontier and research gaps: pastoral, soil P

As the cheapest management practice to decrease diffuse P losses is to maintain soils at economic optimum Olsen P levels, this may mean a reduction in the amount of P fertilisers applied. The development of models to predict how long it will take to reach soil P targets using different methods (e.g. withholding fertiliser at different rates, cultivation, planting forages with greater P requirements) will be beneficial to end-users.

On a larger scale, the impacts on nutrient flows when changing from a dairy farm production system 1 (all grass fed, all on farm) to a system 3 or higher (with increasing feed supplements) has not been investigated in depth. In addition, more long term, and catchment scale studies are needed to compliment paddock and farm measurements to measure the effectiveness of management options.

Nutrient sources: nitrogen and phosphorus

Dung and urine

Dung and urine recycle nutrients via the animal and are an important part of the pastoral system and are key to improving nutrient use efficiency. Given that urine is a major conduit of N loss (gaseous and leaching) from dairy and dry stock systems, nutrient management science has generally focussed on understanding and reducing N losses from urine – and therefore, by inference, improving NUE.

Dung is a more important source of phosphorus. Around 60% of P ingested by grazing stock is excreted back on to the paddock as dung, but the exact figure depends on stock type and the amount of P consumed. The P content of pastures varies throughout the year but is usually greatest in spring. Much of the P in fresh dung is in the available and water soluble form and can be a direct source of P. Dung can also be an indirect source of P in areas with high rates of deposition (laneways, around watering troughs overnight paddocks).

Scientific advances in the period 1998 to 2013; pastoral, dung, urine

Dung

Research has focused primarily on N_2O emissions from dung, to support development of the National Inventory. Research on surface run-off from dung has usually been driven by the need to quantify P loss but also provides data on N. There has been limited research on the interaction of dung patches with soil and implications for nutrient cycling processes.

- *Characterisation - Dung:* There has been some work looking at P fractions in dairy, deer and sheep dung, both fresh and dry, and their contributions to P loss in overland flow. The solubility of P in dung changes as it dries, and because the breakdown of desiccated dung pats is limited, accumulation of dung occurs over the summer. In experiments directly comparing the effects of treading and dung, dung has been found to be a more significant contributor to P losses, although this was also dependant on soil type. However, very little work has been done in New Zealand on the variation in dung-P with different feeding systems.
- *Overland flow:* Losses in overland flow depend on stock type and stocking rate, and decrease with time since grazing. The loss of P from dung is often more significant than P loss from treading alone, but depends on soil type. P losses in overland flow under flood irrigation have been specifically investigated and identified as an important source of P loss. In flood or border dyke irrigation, water is applied at the top of the paddock (confined by earthen borders or banks) and runs down to the bottom. The excess irrigation water is high in nutrients and can be collected and reused, but acts as a source of P loss when discharged to a waterway.
- *Leaching:* Measurements of grazing-related P loss in subsurface flow are limited, but the available data show increased P loads in drainage from paddocks with dairy grazing.

Urine

There has been considerable research effort to measure ('farmlet' experiments) and model N losses at the block or farm scale, with much of the loss associated with urine deposition. Here we consider research at the urine patch scale, however. Earlier research on this topic was summarised by Haynes & Williams (1993). Research in the last 15 years has covered these topics:

- *Urine composition*: few papers on nutrient composition and its variability, nor on implications for urine patch N loading
- *Temporal and spatial distribution*: few papers on this topic
- *N leaching*: lysimeter studies to mimic individual urine patches and interactions with N fertiliser and effluent
- *Gaseous losses*: mainly N_2O losses at the individual urine patch level
- Soil processes: individual studies to understand urine impacts on aspects of the soil N cycle.
- *Controlling losses*: management interventions to decrease N leaching (e.g. wintering off paddock or use of low N feeds) as well as the use of technologies such as DCD to control leaching and nitrous oxide; less emphasis on ammonia to date, although there has been some research on urease inhibitors
- *Modelling processes*: integration of current understanding of soil/pasture processes to model the fate of N in individual patches; also, modelling to scale from patch to paddock.

Knowledge frontier and gaps; pastoral, dung, urine

The importance of the urine patch in pastoral systems as a source of N loss and the key to improving nutrient use efficiency has long been recognised, and this is reflected in the research that has taken place. There is a good understanding of the importance of the urine patch; there is a good understanding of some mitigations to decrease losses and this extends to mitigations that modify the urinary N excretion by animals. Much of the research now is directed at building farm systems that aim to control the urine patch – and this is exciting and invaluable research. However, further systems analysis is required, i.e. improved practices and their integration to increase whole system nutrient use efficiency. There is also a lack of understanding of the long-term implications of mitigations. For example, it could be hypothesised that retained N that would have otherwise been lost from the system then provides feedback and decreases N fixation (more N already available): this could result in a tighter N cycle. Longer-term studies are required to test this.

At the patch scale, we have learnt much from lysimeter studies about fate and transport of N through the soil. However, we have less knowledge on some soil-types, especially stony/shallow/light soils and when combined with irrigation. There is a good understanding of N_2O losses from the urine patch, possibly less so around NH_3 losses as there has been no real driver to control these to date; even though it can represent a significant loss from the system (reduces N use efficiency). As well as limiting the transport of urinary N, further work on modifying the source (through forage or animal management) is also required.

The ability to model urine patch dynamics is good and this has helped extrapolate experimental data and upscale to farm systems level. However, there are still gaps in fundamental understanding of the urine patch which impacts on ability to model and manage pastoral systems: variation in urinary N composition; urine patch size, edge effects (i.e. access to urine by pasture outside of the wetted area); the effect of time and spatial distribution on N leaching. Given the importance of urine, this is surprising.

While nearly all research on N leaching has focused on mineral forms (and urea), dissolved organic N is potentially an important source of leachable N, often associated with urine deposition.. Some consider this is the missing N in a complete nutrient budget, yet it is an under-researched topic area.

Little work has been done in this country to understand the variation in P loads via dung from sheep, beef and dairy, with season and feed.

Effluent

Effluent, slurries and manures are important nutrient sources on NZ dairy farms, especially since the move from 2 pond systems and discharge to the preferred land application. They arise from excreta deposited in dairy sheds, feed pads and holding areas, which is collected and stored before land application. Much of it is handled as a low dry matter (dry matter; <1%) material applied to soils through various irrigation set ups. Slurries and manures have higher dry matter content and are spread by tanker or muck spreaders. Volumes of effluent to be dealt with are increasing (more dairy conversions, increasing stocking rates and more off-paddock wintering of stock).

Scientific advances in the period 1998 to 2013: pastoral, effluent

Modelling, case and catchment studies have demonstrated the benefit of good effluent management to improve nutrient use efficiency and to avoid losses of nutrients and pathogens. Research has focussed on:

- *Characterisation*: research on effluent has been focused on characterising the loads and forms of P (and N) in effluent. It is accepted that these materials are highly variable but guidelines have been developed for ‘typical’ values. There has been some investigation of ‘rapid methods’ to allow on farm estimation of nutrient content (e.g. dry matter content).
- *Leaching/run-off*: recognition of the risk of leaching through structureless soils if nutrient application rate exceeds pasture/crop demand. Understanding of bypass and macropore flow causing rapid movement of nutrients, pathogens and particulates from the soil surface in drained clay soils and/or soils with significant bypass flow. Understanding of surface run-off risk on some soils and topographies. Irrigation appears to increase particulate losses of P though dislocation of soil particles.
- *Application strategies*: this research has underpinned the development of guidelines for safe application of effluent based on soil-type, soil moisture status and topography. These strategies often require more storage space compared with traditional methods of application. The greatest volumes of storage required are found in the south of the South Island and in high rainfall areas where there are limited opportunities to apply effluent safely.
- *Application technologies*: development of application technologies (e.g. irrigators and irrigation systems, solid separation systems) to meet these requirements is now mainly industry led.

- *Other technologies*: The dairy effluent storage calculator (DESC) has been developed to calculate storage requirements based on location, soil type etc. Some work has gone into additions to effluent (e.g. alum, zeolites) before application with the aim of capturing P and then reapplying the medium as a soil conditioner. However, because many of these additions effectively fix P, it is only slowly available once returned to the paddock
- *Other*:
    - Soil health: impacts on soil nutrient accumulation, organic matter, soil microbiology and understanding of impacts on soil nutrient transformations.
    - Agronomy: impacts on pasture/maize growth; fertiliser equivalency of FDE in terms of N contribution.
    - Nitrous oxide and methane emissions.
    - Wastewater treatment systems: covering a range of wastewaters from processing industries but with limited applicability to the dairy industry.

Knowledge frontier and gaps: pastoral, effluent

The main challenge is to manage these nutrients sustainably. Robust advice on application rates and methodologies, differentiating between soil-types and environmental conditions has been developed from a few detailed studies and first principles. The gaps in this advice now relate to a few minor soil-type/environment combinations; the main challenge is now about on-farm uptake, i.e. technology transfer.

Whilst the research emphasis to date has been around delivering (predominantly) liquid effluent safely to soil, the research gaps are now around improving nutrient use efficiency. Diverting urine from paddock to effluent is seen as a key strategy for improving NUE in dairy systems; it is therefore essential that research around effluent management ensures this improvement is realised. Research gaps that need to be addressed to fulfil this are:

- Storage losses of nutrients (N as NH_3, N_2O, all nutrients via leakage from ponds): quantifying losses and their interaction with storage management; and developing mitigations to decrease losses.
- Application technologies: to minimise losses and maximise nutrient use efficiency for the range of materials from liquids to solids.
- Pollution swapping: understanding and minimising transfer of losses from one pathway to another through the effluent/manure management train; for example, decreased nitrate leaching by redirecting urine to effluent but then increasing losses of ammonia and nitrous oxide during storage.
- Fertiliser replacement value of effluent/manure nutrients: e.g. under new spreading techniques; short-term and longer-term release of nutrients.
- Longer-term effects of repeated effluent applications on soil nutrient status, including trace elements.

There is also little information about the impact of NH_3 loss from effluent storage/disposal on biodiversity of predominantly native ecosystems located near farmed areas. Native plant species have evolved to survive and thrive in a low N environment.

Processes: nitrogen cycling: Pastoral

Denitrification

Losses as N_2 can be substantial from pastoral systems, driven by wet conditions and higher temperatures and stimulated by the presence of labile C; the principles are well established. Denitrification represents a loss of nutrient but as conversion to N_2 is environmentally benign, there has been less focus on this process in recent years.

The recent emphasis has been on quantifying and developing mitigations for N_2O loss. Much of this work has been driven by the need to strengthen data in the National Inventory and so there is generally a good understanding of size of losses and factors affecting loss from N sources, as well as development of mitigations. There is less information on nitrous oxide losses from the beef and sheep sector compared with dairy.

In terms of NUE denitrification is more important (potentially more kg N/ha) than N_2O though major emphasis is on N_2O because of its GWP. The impacts of dentitrification on nutrient use efficiency need to be revisited.

Volatilisation

The principle drivers of NH_3 loss are well established. Ammonia is a concern primarily as a secondary source of N_2O although NH_3 losses can be significant and high losses of NH_3 reduce NUE. Technologies have targeted urea fertiliser to improve efficiency of this source. Knowledge around losses from effluents, slurries and manures under NZ situations is lacking. While technologies could target these sources; urine patch volatilisation would be more difficult to target (e.g. analogies with dicyandiamide (DCD)).

Immobilisation and mineralisation

These are important drivers of N cycling through farm systems and a better quantitative understanding of mineralisation-immobilisation turnover (MIT) has long been the goal of soil scientists. Accounting for soil N supply (mineralisation) or soil N depletion (immobilisation) is essential to improve NMS advice. Mineralisation supplements other sources of N inputs and therefore affects fertiliser N requirements. Depletion by immobilisation will increase requirement for supplementation.

There is a broad understanding that ‘development status’ of pastures influences MIT but there is less quantitative understanding of the effects.

The N fixation <u>process</u> is well understood, i.e. legumes fix N in low soil N status. It could be argued that there is a greater emphasis in legumes in dry stock farms where there is less reliance on imported N. Even so, there is a driver for more efficient N use on dairy farms which may lead to lower external N inputs and a greater reliance on fixation.

Many of the issues are not about the process itself, but how to manage the legumes to maintain their presence and their ability to fix N, e.g. grazing and fertiliser management.

Leaching

The physical process of N leaching is understood. In pastoral systems, the emphasis has been on understanding leaching from urine patches. There are still gaps in our understanding, e.g. understanding the process on shallow soils, very wet climates, impacts of excess irrigation.

However, leaching is not just about the physical process, but understanding the factors that influence the size of the mineral N pool in soil available for leaching. We therefore also need to understand the balance with other removal processes (uptake, immobilisation etc.); and the initial size of the urine source is also important, so better knowledge of urinary N load per urine patch, seasonality and variability are key gaps that need to be addressed.

Leaching from N fertiliser can also be considered as 'direct' or 'indirect':

- Direct losses of fertiliser N applied when plant demand is low and there is drainage (e.g. winter)
- Indirect losses via the urine patch where fertiliser N has been assimilated into forage and excreted back on the pasture

Most emphasis to date has been on urinary N sources, but there will be circumstances where N leaching from fertiliser may be important: further knowledge on this aspect is required. And, as stated earlier, an important knowledge gap is around leaching of dissolved organic N and the importance of this for improved nutrient use efficiency.

Sector based analysis of nutrient management science: Forestry

Nutrient sources: nitrogen

N fertiliser

Nitrogen is one of the key nutrient deficiencies limiting forest productivity. Research from the 1960's to the 80's defined areas and conditions under which N deficiency is likely to occur in forests as well as treatment strategies. Application to forests peaked during the 1980's and today little N is applied although it is recognised there remains an opportunity to increase forest productivity by N application on many sites. It is expected that N will become progressively more limiting as new high growth rate clones are deployed and as tree growth responds to increasing CO_2 concentrations in the atmosphere.

Scientific advances in the period 1998 to 2013: forestry, N fertiliser

- *Determining N response pattern*: Trials have been conducted in young and mid-rotation stands with and without P, to determine the likely occurrence and magnitude of response.
- *Impact of N fertilisation on wood quality*: An understanding of the effect of N fertilisation on coastal sands on the density of earlywood and latewood in *Pinus radiata, and* improved understanding of N fertilisation (in combination with other nutrients) on wood properties including modulus of elasticity, wood density and fibre length.
- *Selection of nutrient efficient genotypes*: To reduce N fertiliser requirements, genetic variation in a range of breeding populations and

clones has been investigated to determine if there is scope for selection of genotypes that are efficient in N uptake and use within the plant.

Knowledge frontier and gaps: forestry, N fertiliser

Foliage analysis is used for deficiency detection. The ability to predict deficiency is good when foliar concentrations are low, but requires improvement when concentrations are marginal. Most fertiliser N is tied up in soil organic matter and never reaches the crop. Methods for more efficient application need testing. Traditionally the response value of fertilisation is measured by the volume of additional wood produced; however, it is now realised that fertilisation can alter the value of individual logs and of the products cut from logs but much more research on N fertiliser impact on economic response is needed. Mycorrhizas (symbiotic associations between plant roots and soil fungi) play an important role in N uptake but it is not known if mycorrhizas can be manipulated to enhance uptake of N and reduce N fertiliser requirements. The role of soil microbes in N nutrition is poorly known, and their potential manipulation to improve N uptake and reduce fertiliser reliance requires investigation. Forest growth in New Zealand is predicted to increase as a result of increased atmospheric CO_2 concentrations as well as deployment of high growth rate clones. Studies are required to ensure these potentially higher growth rates are captured and not N limited. New information indicates that N is important in regulating plant gene expression, physiology and growth and development, and the importance of this regulation for key plantation forest species is required.

Key research gaps are seen to be:

- *Prediction of N response*: Evaluating use of environmental variables such as temperature, soil N mineralisation and availability in combination with foliar N concentrations. Understanding of interactions with other nutrients including P, B and Mg. Further development of tools for N fertilisation decision making. The ability to detect deficiency and predict response using remote sensing should also be investigated. Some emphasis should be placed on mid rotation plantations.
- *Application technology*: Research on aerial application using foliar sprays to increase fertiliser use efficiency.
- *Determining the value of N response*: Assessment of fertiliser impacts on logs and log products is needed to improve our understanding of the economic response to N fertiliser.
- *Mycorrhizas*: Knowledge of specific variation in N uptake and manipulation of mycorrhizal populations.
- *N dynamics in new environments*: Understanding of N response in high CO_2 environments and by high growth rate clones.
- *Role of N in regulating physiology and growth.* Study of the importance of N in gene expression, physiology and growth and development of *P. radiata* is needed.

N fixation by legumes

The legume *Lupinus arboreus* played an important role in development of large areas of N deficient coastal sand forests in New Zealand through improving soil N levels. The arrival of a fungal pathogen disease in the early 1980’s decimated the lupin population and it’s use for N fixation in coastal sand forests ceased. Trials to select species to replace lupin have been undertaken, however suitable species have yet to be deployed. In other forests, the pasture legume *Lotus pedunculatus* has been used intermittently to improve soil N levels and forest productivity. Shrub-weed legumes (gorse and broom) compete strongly with establishing tree crops in many areas and require considerable resources for their control. Their weed potential is seen to outweigh benefits that arise from N fixation.

Scientific advances in the period 1998 to 2013: forestry, legumes

- *N-fixers to replace lupin*: N-fixing species have been screened in field trials as potential replacements for lupin in coastal sand forests. Studies have included species comparisons of survival, height growth, diameter spread and N-fixing ability. Establishment by seeding and planting have been examined as have the effects of different growth media on seedling growth and nitrogenase activity.
- *P dynamics in legume-pine systems*: Comparison of dynamics of different P fractions in soil under pine and lucerne grown alone and in combination in a silvopastoral system.

Knowledge frontier and gaps: forestry, legumes

While progress has been made in selection of N-fixers for coastal sand forests, to date there has been no deployment of selected species. Investigation into the reasons for this is required. Increasing atmospheric CO_2 levels are expected to favour legume growth and N-fixation and this is likely to have implications for the forest industry which require investigation:

- *N-fixing shrubweeds*: An understanding of how CO_2 may impact on N-fixing shrubweed growth, N-fixation, and N leaching and the control of these species is required.
- *Using 'pasture' legumes in forests*: There is potential for using pasture legumes (or other non-weed N-fixers) in forests other than those on coastal sands for improving soil N levels, this potential is likely to increase with increasing CO_2. Studies of incorporating N-fixers at stand establishment, and potential benefits through N-fixation and increasing crop growth are required.

Nutrient sources: phosphorus

P fertiliser

Phosphorus is an important element limiting forest productivity on strongly weathered soils in the tropics and sub-tropics. The New Zealand representatives of these types of soils – the podzolised sands and clay soils in Northland, North Auckland and the Coromandel peninsula – were extremely P deficient in the past, but P fertilisation has alleviated the deficiency in many forests. Elsewhere, P deficiency may limit forest productivity on a range of soils in both North and South Islands. As with other nutrients, P deficiency is recognised mainly be by foliar analysis. As with N, it is expected that P will become progressively more limiting as new high growth rate clones are deployed and as tree growth responds to increasing CO_2 concentrations in the atmosphere.

Scientific advances in the period 1998 to 2013: forestry, P fertiliser

- *P response in mid-rotation P. radiata*: Trials have been conducted in North and South Islands in mid-rotation *P. radiata* stands, with and without N, to quantify the occurrence and magnitude of response.
- *Predicting P response in young stands*: Determining relationship between soil extractable P and growth response in 4-year-old stands, and influence of soil type, weed control and cultivation on response relationships.
- *Residual effects of P fertilisation*: Determination of whether operational P levels applied in one rotation has long term effects on P supply through to next rotation, and need for re-fertilisation.
- *Availability of different P fertiliser forms*: Comparison of growth and foliar P response to soluble (TSP) and less soluble (rock P). Determination of relationships between foliar P and soil P tests. Impact of P fertiliser forms on soil P fractions, and downward movement of P in the soil. Interactions of P fertilisation and understory species.
- *P application at planting*: Comparison of seedling response to different P fertiliser types and application techniques (in-soil vs broadcast).
- Other
    - *Soil P dynamics in silvopastoral systems*: Examination of spatial and temporal variation of soil P dynamics and availability in silvopastoral systems with different understory pasture species.

Knowledge frontier and gaps: forestry, P fertiliser

The role and use of different P fertiliser types in different environments is relatively well understood. Prediction of P response from foliar P analysis is good, whereas prediction of response from soil analysis is poor. Tree species that form ectomycorrhizas (mycorrhizas where the fungal hyphae form a mantle around roots and a net between root cells) (e.g. *P. radiata*) can access soil organic P fractions but this is not determined in soil P measurement procedures used for predicting P response. Otherwise the knowledge frontier and gaps for P are essentially the same as for N, viz: lack of understanding of the economic response in terms of logs and log products, lack of information on potential to manipulate mycorrhizas and microbes to enhance P availability, and lack of understanding of P limitation of potentially higher forest growth rates from high growth rate clones and increased atmospheric CO_2 concentration.

Key research gaps are seen to be:

- *Importance of soil organic P*: Development and testing of soil test procedures that include appropriate organic P fractions is needed.
- *Determining the value of P response*: Assessment of fertiliser impacts on logs and log products is needed to improve our understanding of the economic response to P fertiliser.
- *Mycorrhizas*: Knowledge of specific variation in P uptake and manipulation of mycorrhizal populations.
- *P dynamics in new environments*: Understanding of P response in high CO_2 environments and by high growth rate clones

Nutrient sources: nitrogen and phosphorus:

Mycorrhizas and soil microbes

It has long been known that mycorrhizas are important for facilitating nutrient uptake, especially of P. International literature in the last 30 years has shown that ectomycorrhizas, as formed by key plantation conifer species (pines and Douglas fir) are better able to access N and P from soil organic sources than species forming arbuscular mycorrhizas (mycorrhizas where fungal hyphae form structures within root cortex cells) (eg redwood, cypress, as well as pasture and crop species). This knowledge has not been fully exploited in forestry. More recently it has been realised that understanding lesser known interactions between plants and soil microbes may allow development of new approaches for enhancing nutrient availability and improving production.

Scientific advances in the period 1998 to 2013: forestry, N&P, myccorhizae and microbes

- *Mycorrhizal dissolution of rock P:* Impacts of rock P on mycorrhizal formation in *P. radiata*. Impacts of mycorrhizal activity on P dissolution, phosphatase enzyme activity, (enzymes produced by plant roots and microrganisms capable of converting some organically bound P forms into phosphate ions that can be absorbed by plant roots) acidity and soil P fractions in the rhizosphere. Effects of mycorrhizal inoculation on rhizosphere properties, P uptake and seedling growth.
- *Species mixtures to enhance nutrient availability*: Understanding nutritional effects of growing tree species with ecto- and arbuscular mycorrhizal types in mixtures and whether N and P uptake of arbuscular mycorrhizal species can be improved when in mixture with ectomycorrhizal species.
- *Site disturbance effects on mycorrhizal colonisation*: Understanding site disturbance effects including forest floor and mineral soil removal and soil compaction, associated with timber harvesting, on mycorrhizal colonisation and ^{15}N uptake.
- *Nursery management impacts on mycorrhizas*: Impacts of fertilisation and fungicide use in the nursery on seedling and out-planted stock root mycorrhizal assemblages, and seedling growth and nutrition.
- *Harvesting impacts on microbial biomass*: Quantification of the long-term effect of organic matter removal during harvesting on microbial biomass N and net N mineralisation.

Knowledge frontier and gaps: forestry, N&P, myccorhizae and microbes

While the beneficial effects of mycorrhizas on tree species nutrition has been known for many years, little research has been undertaken on how mycorrhizas or soil microbes are affected by management practices, or may be manipulated to improve forest nutrition. An improved understanding of interactions between plants, mycorrhizas, microbes and soils is needed. Potential research areas include:

- *Management impacts*: An understanding of the longer term impacts of management practices, especially of nursery and forest chemical usage, on mycorrhizal species and development as well as the microbial population is required.
- *Mycorrhizal species*: An understanding of N and P absorption by different mycorrhizal species is needed, and whether there is scope for species manipulation to enhance nutrient absorption.

- *Microbes*: Knowledge on the links between soil microbes, tree nutrition and vigour, and plant immune system response. How can plant growth promoting rhizobacteria activity be enhanced in forest soils?
- *Species mixtures*: Further information is needed on the effect of mixing species, including understory species, with different types of mycorrhizas on host species nutrition.

Biosolids

Biosolids are treated sewage sludges that have been stabilised to the extent that they are able to be safely and beneficially applied to land. In New Zealand, about 77,000 dry tonnes of municipal biosoilds are produced annually. Biosolids are rich in both organic matter and essential plant nutrients and can be utilised as a soil amendment and fertiliser. Biosolids act as a soil amendment through the contribution of organic matter. Biosolids serve as a fertiliser by providing essential macronutrients (e.g. N, P and potassium) and micronutrients (e.g. zinc, copper and iron) that increase plant growth and productivity. The stabilized biosolids provide a slow release source of nutrients that can be utilized by plants for several years following application. The slow release of nutrients prevents leaching of excess plant available nutrients and possible contamination of ground and surface water.

However, the level and nature of contamination in biosolids varies, and our knowledge of contaminant bioavailability and contamination potential is still evolving. Biosolids contain heavy metals and potentially toxic or eco-toxic substances, which require careful management. One of the main barriers to large scale land application of biosolids has been negative public perception and uncertainty surrounding the fate of heavy metals and persistent organic pollutants in the environment.

Beneficial use of biosolids as a supplemental fertiliser and soil amendment is one of the most common options for biosolids management (Magesan and Wang 2003). In New Zealand, application of biosolids on forest land is preferred than on agricultural land because it can reduce the risk of contaminants entering the human food chain and it can also increase tree growth and subsequent economic returns (Kimberley et al. 2004; Wang et al. 2006).

Scientific advances in the period 1998 to 2013: forestry, biosolids

Case and long-term studies have demonstrated the benefit of sustainable biosolids management to improve site and forest productivity and to minimise environmental impact. Research has focussed on:

- *Characterisation*: it is recognised that biosolids are highly variable due to different sources and treatment technology of wastewater. The ‘typical’ values” of biosolids constituents can been found in NZ biosolids guidelines. Extensive survey results indicate that concentrations of contaminants in New Zealand biosolids are generally low (Ogilvie 1998; McLaren et al.1999) and normally do not limit the beneficial use of biosolids (NZWWA 2002). Municipal biosolids usually contain high concentrations of N, and hence, N loading is usually used as a limiting factor when a system is designed for land application (NZWWA 2002).

- *Leaching/run-off*: recognition of the risk of leaching through structureless soils and contamination water bodies if biosolids application and N mineralisation exceeds the assimilation capacity of the ecosystem. Understanding of bypass and macropore flow causing rapid movement of nutrients, pathogens and particulates from the soil surface in drained clay soils. Understanding of surface run-off risk on some soils, topographies and weather conditions.
- *Long-term impact:* On limited soil types, this research has investigated the impact of long-term application of biosolids in forests on soil and groundwater quality. Recognition of the risk of detrimental effects of accumulated nutrients and heavy metals on soil and groundwater contamination.
- *Good management practice*: this research has underpinned the development of guidelines for safe application of bioslids based on topography, soil-type, ease of biosolids transportation and access to forest sites, vegetation and tree capacity to use biosolids-derived nutrients, biodiversity, buffers to waterways, climate, on site storage and community.
- *Application technologies*: development of application technologies, including application methods, rate and timing, nutrient and contaminant loading limits, silvicultural management to meet the safe application and beneficial use of biosolids by the guidelines.
- *Other*:
    - Soil health: effects of heavy metal and persistent organic pollutant on soil nutrient transformations, biological and microbiological biodiversity and functions.
    - Tree nutrition and health: Greater beneficial effect on tree nutrition and growth.
    - Wood quality: some minor negative effect on wood density and stiffness.
    - Economic benefit: substantial economic return due to stem volume growth.

Knowledge frontier and gaps: forestry, biosolids

The management practices for forest land application of biosolids have been developed from a few detailed studies. The gaps in the current management practices relate to a few minor soil-type/environment combinations. In addition, the level and nature of contamination in biosolids varies, and our knowledge of contaminant bioavailability and contamination potential is still evolving. Biosolids may contain potentially toxic or eco-toxic emerging substances, which require careful management. New scientific solutions to these challenge need to developed. Robust management guidelines on application rates and methodologies for different soil types, silvicultural regime and environmental conditions are also required for forest land users.
Research gaps that need to be addressed to fulfil this are:

- Long-term impact of accumulated heavy metals and their interaction with emerging contaminants on ecosystem biodiversity and functioning.
- Reduce or mitigate the risk of emerging micro-contaminants found in biosolids.
- Consequences for soil carbon sequestration and storage; a greater understanding of the effects of biosolids addition on soil processes in relation to carbon turnover and sequestration.

- Storage losses of nutrients (N as NH_3, N_2O, all nutrients via leakage from ponds): quantifying losses and their interaction with storage management; and developing mitigations to decrease losses.
- Application technologies: to minimise losses and maximise nutrient use efficiency for a range of biosolids applied in different forests and soil and climatic conditions.
- Biosolids application decision making tool: A user-friendly tool for management of land application of biosolids in forests.

Nutrient sources: Boron

B fertiliser

Boron deficiency is important in drier areas of the forest estate where it occurs periodically during dry summers. Boron deficiency causes stem malformation and has a large impact on economic return and foresters tend to apply B as insurance in drier areas to prevent its occurrence. Early work established areas of occurrence and fertiliser strategies to prevent development of B deficiency. With climate change, eastern regions are expected to experience more extended dry periods and droughts which will increase the occurrence of B deficiency.

Scientific advances in the period 1998 to 2013: forestry, B fertiliser

- *Interactions with weed control and genotype*: Fertiliser trials have been undertaken to refine application rates for *P. radiata* and examine interactions between fertilisation, weed control and genotype.
- *B deficiency and Douglas fir*: Fertiliser trials to examine relationships between B and occurrence of malformation in Douglas fir.
- *B deficiency and tree health and wood quality*: Examination of links between B deficiency and resin bleeding and internal checking.

Knowledge frontier and gaps: forestry, B fertiliser

There is a good general understanding of soils and climates under which B deficiency may occur, but within these bounds we are unable to accurately predict when B deficiency will develop. Prediction of occurrence would be improved with a better understanding of the connection between soil moisture availability and B deficiency. Some understanding of the effect of B fertilisation at low rates on wood properties has been gained but no information is available for higher rates of application. New focus is being placed on the potential for *Eucalyptus* species for drier areas but little is known about *Eucalyptus* species and B deficiency in New Zealand. International literature is indicating links between B deficiency and tree health and disease incidence, but New Zealand studies are lacking. Research required to fill these gaps should focus on:

- *Predicting B response*: Research to improve our understanding of the connection between soil moisture availability and B deficiency occurrence
- *Eucalyptus species*: Examination of potential importance of B deficiency in dryland *Eucalptus.*
- *Wood quality*: Examination of the impact of higher application rates of B fertiliser on wood properties such as resin bleeding and internal checking. Examination of the potential of B to improve cell wall strength, and of later age application to increase pectin cross linking in cell walls.

- *Tree health*: New studies are required to establish if B is linked with plant immune system responses and overall plant health.

Processes: nitrogen cycling

N leaching

Nitrogen concentrations in streams draining forest plantations are typically lower than that of other major land uses, and forests have a role to play in provision of high quality water in sensitive catchments (e.g. Lake Taupo) and improving water quality arising from pastoral or cropping land uses. Most plantations were established after removal of indigenous vegetation but since the 1960's many plantations have been established on ex-pasture sites. Nitrogen concentrations in streams draining forests depend on land use history, and may also be influenced by the presence of leguminous shrub weeds (gorse, broom) which may leach considerable amounts of nitrate. Fertilisation to improve forest productivity has the potential to increase nitrate levels and reduce drainage water quality.

Scientific advances in the period 1998 to 2013: forestry, N cycling

Catchment and lysimeter studies have been used to examine land use, shrub-weed and fertiliser impacts on N leaching from forests. Research has focussed on:

- *Change in N leaching with forest development*: Catchment and lysimeter studies have examined changes in N leaching from forests planted on ex-pasture sites from the time of establishment through to first harvest and beyond.
- *Quantification of leaching from associated weeds*: N leaching from gorse in Lake Rotorua catchment has been quantified.
- *Impact of N fertilisation*: An improved understanding of the effect of edaphic factors, land use history and presence of N-fixing species on the leaching response to N fertiliser has been obtained.

Knowledge frontier and gaps: forestry, N cycling

A better understanding of factors influencing N leaching from plantation forests has been obtained, and the work has indicated practices that could help reduce N loss on particular soils and at particular times in the plantation cycle. Gaps remain around how best to integrate forests into catchments containing other land uses with large N footprints to get greatest reductions in N leaching without compromising productivity, and potential forest management strategies that might reduce N leaching. Research gaps that need to be addressed include:

- *Understanding of riparian plantings on N losses to streams*: quantifying losses in relation to tree species and stand management practices.
- *Denitrification zones*: development and testing of streamside wetland denitrification zones using wetland tolerant tree species such as redwood.
- *Nutrient balance modelling*: Further development of a nutrient balance model capable of predicting changes in soil N capital under various site and management conditions and identification of optimum management strategies for new forest stands is required.

Outcome focus: Sustainability
Nutrients are removed from the site when forests are harvested. The amount of nutrients removed depends on harvest intensity. Harvest intensity is likely to increase if biomass is harvested for biofuel production. Site disturbance at harvest caused by removal or displacement of the forest floor or upper mineral soil, and replanting management practices such as v-blading and mounding also impact on soil nutrients. Harvest nutrient removals and site disturbance have implications for long term sustainability, especially as many forests are now in the third, and some in the fourth rotation. Understanding of impacts of management practices on sustainability has required development of sustainability indicies.

Scientific advances in the period 1998 to 2013: forestry, sustainability

Field studies have examined the impacts of harvesting and site preparation practices on soil nutrients. Novel small plot studies with high tree densities covering the full range of climatic and edaphic environments within the New Zealand plantation forest estate have been undertaken to rapidly identify potential indicators of sustainability. New trials are examining genotype x environment interactions for N, P and other nutrients. Research has focussed on:

- *Harvesting impacts*: Understanding long term Impacts of increasing harvesting intensity, including whole tree harvesting and forest floor removal, on organic and mineral soil characteristics and long term site productivity
- *Site preparation impacts*: Quantification and understanding of impacts of different site preparation methods on soil N.
- *Soil indicators*: Key soil indicators influencing the growth of key plantation forest species have been identified.
- *Genotypic x environment interactions*: Understanding how species and genotypes within species vary in response to different nutrient limiting conditions. Establishing the pattern and extent of genetic variation and the scope for selection for nutrient use efficiency.
- *Nutrient balance model*: A nutrient balance model has been developed to predict biomass and N pools in *Pinus radiata* forests that allows management techniques to be optimised for productivity and nutrient pool retention over single or multiple rotations.
- *Nutrient release by weathering*: Quantification of nutrients released by weathering in representative multi-rotation forests by modelling and soil nutrient extraction. Relating nutrient supply to nutrient removal at harvest.
- *Short rotation forestry*: Impacts of tree density and tree species on biomass production, litterfall & nutrient cycling in short rotation *Eucalyptus* crops.
- *Impact of multiple rotations on P fertility*: Examination of multiple rotations and associated soil disturbance on soil extractable and foliar P concentrations.
- *Availability of different forms of soil P*: Determination of availability of different forms of soil P, including organic P fractions to species with different mycorrhizal types.
- Other
    - *Litter decomposition*: Understanding decomposition dynamics and nutrient release of green and fallen needles, and coarse woody debris. Effects of mixing understory species litter on needle decomposition. N and P mineralisation of litter in windrows and

disturbed soil. Understanding ecosystem N status on residue decomposition.
- o *Biomass production, litterfall & nutrient cycling in eucalypts*: Impacts of tree density and species on nutrient cycling in short rotation eucalypts

Knowledge frontier and gaps: forestry, sustainability

A considerable bank of knowledge on impacts of management practices on forest sustainability has been developed in recent years and foresters have by and large adopted sound sustainable management practices. However further understanding of the impacts of harvesting on nutrient removals is required. Incorporation of measurement of sustainability indicies into forest management is still required. A challenge remains in getting the sustainable nature of the forest industry across to the general public. The comparative efficiency of different genotypes in nutrient uptake and use requires further investigation to determine if nutrient efficient genotypes can be selected and deployed. Further gains can be made in the following areas:

- *Nutrient removals at harvest*: Determination of impact of different site management practices on removal of nutrients when plantations are harvested.
- *Mycorrhizal and microbiolgical enhancement of nutrient availability*: Improving understanding of interactions between plants, mycorrhizas, microbes and soils to enhance nutrient availability.
- *Nutrient balance modelling*: Further parameterisation and validation of the nutrient balance model is required to improve prediction of nutrient supply and demand and impacts on productivity, and for such uses as predicting impacts of management practices on catchment nitrate leaching.
- *Nutrient use efficiency*: Further examination of genotypic variation in nutrient use efficiency and selection of nutrient efficient genotypes for specific situations.

Sector based analysis of nutrient management science: Arable, Horticultural and Forage crops

Background

The major crops grown in New Zealand are generally categorised as arable, forage, vegetable, or perennial fruit and vine crops. The arable sector is dominated by the production of cereal grains, pulse crops and specialty seed crops. Forages include a wide range of arable and Brassica feed crops grown for livestock grazing during periods of low grass production. Vegetables include fresh and processed crops. The largest perennial tree and vine crops are kiwifruit and apples. There are an increasing number of mixed cropping enterprises that grow a combination of arable, process vegetable and supplementary feed and forage crops. This complicates attempts to maintain the capital reserves of nutrients and predict the supply of nutrients from mineralisation and solubilisation, and estimate nutrient losses.

Arable crops
Broad acre arable cropping is dominated by cereal grains and pulses. The main arable crops produced in New Zealand are wheat, barley, oats, maize, peas, and wide range of high value seed crops (brassica, grass, and white clover seeds).

N fertiliser
The nitrogen requirements of arable crops can vary substantially depending on species, target yield, and end use. Yields of the main crops have generally been increasing over time and therefore there has been an ongoing need for research on N management to meet crop demands while minimising the risk of N losses to the wider environment.

Scientific advances in the period 1998 to 2013: arable, N fertiliser

- *Nitrogen to meet crop yield targets*: The quantities of N that cereal crops need to take up at different growth stages in order to achieve a particular yield target are reasonably well understood   In wheat, for example, stem extension (growth stage 31-51) is the growth phase with most rapid N uptake; a crop with high yield potential may accumulate over 5 kg N/ha per day during this phase.
- *Predicting soil N supply*: The best estimates of the amount of N that can potentially be mineralised from cropping systems during the growing season vary substantially (range <50 to >200 kg/ha per annum) depending on land management history and other factors including weather variables (temperature, rainfall).
- *Nitrogen scheduling*: Field trials carried out in the last 15 yr or so (mostly in Canterbury) have provided valuable information on scheduling of N applications (amounts and timing) to optimize yield and quality (protein) of wheat and barley
- *Wheat calculator*: A nitrogen (and irrigation) scheduling decision support system (DSS) for wheat (based on a wheat growth simulation model) was developed and tested on-farm during the 2000s. This DSS (*Wheat Calculator*) was shown to give accurate predictions of crop yield and response to N in most cases. Growers and fertiliser advisors have incorporated lessons from the tool into their crop management decisions, but relatively few use the DSS on a regular basis.
- *Maize calculator*: AmaizeN, a DSS to help maize growers schedule N fertilizer applications for site-specific maize crops, was developed and tested. It forecasts crop yields and N-fertilizer application rates for potential yield and best economic returns, and predicts the consequences of user management decisions. It takes into account both crop production and environmental impactOnly a small number of growers actively use AmaizeN, though the tool is also available to fertiliser advisors.
- *Fertiliser for grass seed crops*: Fertiliser N requirements for grass seed crops have been substantially reduced as a result of recent research. Excessive, or poor timing of N, will cause excessive vegetative bulk, increased disease susceptibility or lodging which reduce pollination and light interception.
- *Crop residues as a source and sink of N*: Cereal residues (which often contain 6-10 kg N/t) are potentially a significant N source for the following crop. However, about 40% of cereal crop residues are burned annually in

New Zealand, particularly in Canterbury (home to 70% of New Zealand's arable crops), and much of the N in crop residues *can be lost on burning.* The challenge for farmers is to manage residues in a way that maximises their benefits (including the N benefit) while minimizing problems associated with their retention (e.g., important that un-decomposed residues do not hinder mechanical operations, such as seed drilling or establishment of high value small seeded crops). As high-yielding cereal crops produce large quantities of residues, there has been considerable research effort to identify management practices that promote their rapid decomposition. Production of small seeded, high value crops makes a much more significant contribution to the economic sustainability of arable farming in New Zealand than in countries where residue burning is not practised. Strategic use of residue burning has therefore become more commonly used in New Zealand to deal with the large amounts of residue produced by the cereal crops that commonly precede small-seeded crops in the rotation. The role of post-harvest residues in maintaining soil C has been also extensively researched but little work on the extent and timing of N release from decomposing residues

Knowledge frontier and gaps: arable, N fertiliser

It is well accepted that crop fertiliser N requirement is inversely related to the N supplying capacity of the soil. Difficulty in predicting the quantity of N that mineralises during the growing season continues to be a major source of uncertainty in making N fertiliser recommendations for arable crops. A rough approximation of mineralisation potential can be obtained from paddock management history; however, recent research has shown that mineralisation potential can vary considerably over short spatial scales (within paddock). Identification of a reliable and cost-effective method of estimating N mineralisation potential would represent an important advance in N management science. Additionally, many growers have shown a reluctance to use complicated DSS tools to manage N fertiliser requirements of arable crops. Identifying the best methods and appropriate pathways to disseminate new knowledge is essential to ensure future efficiency gains are realised. This may include intermediary approaches to help guide real-time N management decisions (e.g. biosensors, quick tests).

P fertiliser

Scientific advances in the period 1998 to 2013: arable, P fertiliser

- *Soil P Optima*: Soil P fertility optima (Olsen P) for arable crops are mostly based on historic research and have not been significantly revised in the last 10-20 yr. An Olsen test of 20-25 mg/L is considered optimal for cereals even though a P response is unlikely if Olsen P > 15 mg/L. Recommended practice where the Olsen value is in optimal range is to apply enough fertiliser P to replace the P removed by cereal crops. This implies that P use efficiency is high in cereal cropping systems (P input ~ P output) Appropriate threshold limits will be influenced by the range of crops and pastures grown in farming rotation.
- *Excess P availability*: For some seed crops, high soil P availability is undesirable because it promotes excessive vegetative growth. Field research in the past 20 yr suggests that an Olsen test of 10 mg/L is

adequate for white clover seed crops. Seed yield may decrease when Olsen P is > 15 mg/L because of increased canopy size and stolon shading.

- *P response in peas*: Research in NZ confirmed that pea crops will respond to P only when soil available P is low (yield responses not obtained when Olsen P > 10 ml/L).

Knowledge frontier and gaps: arable, P fertiliser

- *Mineralisation of P*: Mineralisation may be a significant source of P for crop growth but the contribution of mineralised P is extremely difficult to quantify. As a result, P mineralisation is not explicitly considered in making P recommendations for crops. We do not know, for example, to what extent (if any) fertiliser P application rates should be modified depending to land-use history.
- *P in crop residues*: Recent P speciation work suggests that much of the P in above-ground cereal residues is in a form that is immediately available to plants (water soluble orthophosphate). The effect of residue management practices (removal/burning/incorporation) on crop P requirement warrants further research.

Nutrient cycling: Nitrogen and phosphorus

Scientific advances in the period 1998 to 2013: arable, N&P cycling

- *Nitrate leaching losses*: Several studies have reported nitrate leaching losses from arable cropping systems, particularly in Canterbury. Early studies reported low levels of N losses (0-14%) from ^{15}N-labelled fertiliser applied to wheat and ryegrass seed cropping systems. Other studies have used soil solution sampling techniques and lysimeters to estimate leaching losses. These studies suggest that, on average, nitrate leaching losses from arable cropping systems are reasonably low but can vary substantially from year to year depending on autumn residual mineral N levels, cover crop management and the rates and distribution of winter rainfall. Available data sets could be used to validate leaching loss predictions from crop systems models and nutrient budgeting tools like OVERSEER.

Knowledge frontier and gaps: arable, N&P cycling

- *N_2O emissions and Denitrification*: There have very few studies of denitrification losses (N_2 and N_2O) from cereal cropping systems in NZ. Studies with ^{15}N fertiliser suggest that total N losses from arable cropping systems are relatively low. Most have assumed that nitrate leaching losses are very low and that unaccounted for N losses were attributed gaseous emission (N_2 and N_2O). However, direct measurements of these losses are very limited for arable cropping systems.
- *Losses of P in run-off*: There are no available data on losses of P in runoff from arable cropping systems in NZ. Presumably losses are low because most arable crops are grown on flat land and fertiliser P is mostly incorporated. Quantification of P runoff from arable crops on sloping land can be justified to scope its significance and identify the need for mitigation measures.

Vegetable crops

A wide range of fresh and processed vegetable crops are grown across New Zealand, especially in key production regions such as Canterbury, Hawke's Bay, Auckland, Manawatu-Wanganui and Northland. The most common vegetables by area are potatoes, peas, squash, sweet corn, onions, brassicas and carrots. Comparatively few vegetables are grown in continuous, mono-crop production systems. Instead, most growers have multi-crop, multi-year rotations to manage economic risk, weeds, pests and diseases. Nutrient use in vegetable production systems is typically higher than in other sectors, reflecting the high crop value and short crop durations (often less than 6 months). In most cases, if a nutrient deficiency is observed it is too late to address it within the current crop cycle. The obvious exception to this is in covered crops, where a mix of hydroponic and fertigation (applying nutrients in irrigation water) approaches allow almost instant manipulation of nutrient availability.

Nutrient sources: nitrogen

Nitrogen use in vegetable crops is typically high to ensure that yield and quality outcomes are maximised. Although crop N uptake is high, large amounts of N are often returned to the soil in plant residues after harvest. In conventional cropping systems most N is supplied from synthetic fertiliser sources - either mixed formulations including other nutrients (e.g. P, K and trace elements) that are applied before or at planting, or N-rich products (e.g. urea) that are applied during the season. Fertiliser N is often favoured in these systems because it provides a quick and reliable source of N. The use of N-fixing legumes and N-rich amendments such as compost and/or manures typically requires a longer term view to building and cycling nutrients in the soil. These techniques are more common in organic systems where N availability is often a major constraint to productivity. In conventional and organic systems N is also supplied from the ongoing mineralisation of organic matter. While many soils used for intensive cropping are often characterised by low levels of organic matter (and therefore low mineralisation potentials) there can be large temporal and spatial patterns reflecting previous crop management practices and crop rotations. N mineralisation following long term grassing phases can be particularly high.

Scientific advances in the period 1998 to 2013: vegetables, N fertiliser

- *Fertiliser N requirements:* The aim of many trials has been to identify optimum N fertiliser rates for productivity. Interactions between rates, fertiliser timing, form of N and method of fertiliser application have been considered. The key management practices that have evolved from these and earlier trials include: 1) using soil N tests to adjust fertiliser rates and avoid over supply, 2) using decision support tools to guide N management practices and minimize residual soil N at harvest, and 3) planting cover crops during high risk periods to minimise leaching of residual soil N.
- *N x quality interactions:* There have been a few targeted trials on interactions between N supply and crop quality indicators (e.g. N supply and volatiles in onions, N and storage quality in squash and some leafy greens). In many cases the experiments were inconclusive and have not been published.

- *Leaching losses:* An ongoing concern for growers and regulatory authorities has been large N leaching loses quantified under some intensive vegetable systems. This has lead to renewed calls for advanced tools and recommendations that allow growers to more accurately predict and manage N supply dynamics. Two of the key challenges in achieving this have been: 1) difficulties predicting how much N a crop needs and when during the season it needs it, and 2) how much N is supplied from the soil and when during the season it is available.
- *Crop N demand:* Quantifying crop N demand is complicated by dynamic climate conditions (temperature, radiation and rainfall) and intermittent pressures like pests, disease and weeds. These factors can influence crop productivity and therefore N demand. However, these events are difficult to predict, and many N decisions are made early in a crops growth cycle. Some experiments have highlighted opportunities to reduce these risks through split N fertiliser applications. There have also been a number of trials undertaken on winter cover crops to reduce the risk of excess soil N being leached during periods of high rainfall.
- *Soil N supply:* Predicting residual and seasonal N supply from soils remains a significant challenge. While there are established analytical tests to measure residual mineral N (i.e. the fraction of N that is immediately plant available) values can be highly variable - both spatially and temporally within and between paddocks. There are few reliable, quick and cost-effective tests for predicting the potentially mineralisable N (i.e. the fraction of organic N that will be mineralised to plant available forms through biological soil processes under optimal conditions). A number of different analytical proxys have been suggested, though most are not strongly correlated with actual field mineralisation where moisture and temperature can vary substantially.
- *Organic systems and covered crops systems:* There is only a small base of national literature on nutrient management in organic or covered crop production systems. For organics this reflects the small area planted using this approach, whereas for covered crops this reflects the availability of an extensive international literature base and associated technologies from Europe.

Knowledge frontier and gaps: vegetables, N fertiliser

- *Reliable, real time methods to predict crop N demand:* Accurately forecasting nutrient demand is the first step in preventing instances of under or over application, both of which can influence key economic and environmental indicators. Advanced crop models and sensor technologies may assist in these predictions. These tools should provide fertiliser recommendations not only for maximum yield potential but also the most economic rates.
- *Predicting soil N mineralisation:* A stronger quantitative understanding of the soil, climate and management factors that affect N mineralisation over a growing season (as well as in real time) is needed to lift the nutrient use efficiency of intensive vegetable production systems.
- *Intermediary tools for guiding N fertiliser decisions:* In many cases advanced models and DSS tools are not being widely used to make tactical nutrient management decisions because of cost and accuracy concerns. Instead, recommendations based on prior experience or static fertiliser

rates derived from pre planting soil N levels are used - both can be prone to large errors. Intermediary approaches to help guide real-time N management decisions may provide a middle ground (e.g. biosensors, quick tests).

- *Spatially explicit modelling platforms:* Spatially explicit approaches to managing N that allow real time assessment of N availability, interpretation of likely crop responses to further application, and systems to apply variable fertiliser rates where appropriate.
- *Whole-of-farm forecasting tools:* Such tools will help growers and regulatory authorities to predict and manage long term nutrient dynamics in complex cropping rotations. Vegetable systems are increasingly integrated with other cropping enterprises (e.g. arable, forages) which can influence nutrient cycling.
- *Biological farming systems:* The sector is increasingly interested in ‘biological’ approaches that reduce synthetic fertiliser use. The role of microbial communities in N supply dynamics is an area of increased activity. Similarly, the role of N-fixing legumes and/or use of municipal composts may allow further reductions in fertiliser use.
- *NUE benchmarking:* There are no accepted benchmark indicators for NUE across vegetables crops. It is therefore difficult to monitor the impact of changing N management practices.

Nutrient sources: phosphorus

Phosphorus demand in many vegetable crops is minor (20-50 kg/ha) compared to other macro nutrients like N and K (commonly 200-400 kg/ha). However, P remains an essential element in key plant processes and is therefore applied in modest amounts by many vegetable growers before or at planting. Almost all P is applied as synthetic fertiliser P, though some growers use less soluble forms (e.g. rock phosphate) or organic amendments (e.g. fish meal and composts). There are comparatively few intensively managed vegetable soils that have low P availability, largely a function of regular applications above the rate of P removal in the harvested product.

Scientific advances in the period 1998 to 2013: vegetables, P fertiliser

- *Fertiliser P requirements:* Most experiments on crop yield responses to P fertiliser rate and form were conducted >15 years ago. Broad agronomic thresholds have been identified for most vegetable crops and are cited by soil testing laboratories across NZ. In general, these thresholds are much higher than arable and forage crops despite similar P uptake values. The scientific basis for these higher threshold values needs to be clarified .
- *Interactions between soil P availability and soil characteristics:* Experiments have shown that the responsiveness of crops to P fertiliser application can be complicated by intrinsic soil characteristics (e.g. soil P retention and anion storage capacity). These issues tend to be prevalent in specific regions due to the parent material in the soil.
- *P applications above agronomic thresholds:* Many vegetable growers still routinely apply P fertiliser beyond threshold values. This can lead to a gradual enrichment of soil P levels. Three key drivers influence this practice. Firstly, the historically low cost of P fertiliser is outweighed by the risk of crop failure, so fertiliser application is seen as an ‘insurance policy’. Secondly, because P is not easily leached, over-application has been

viewed by growers as an investment in soil capital for the future. Finally, a few trials have shown small responses to P fertiliser above common crop thresholds which has encouraged ‘insurance’ applications. Key factors influencing these crop responses above agronomic norms often relate to cool-wet soil conditions or compacted/pugged soils. These factors combine to reduce the amount of plant available P in solution and also crop root growth.

- *Relationships between high soil P levels and productivity:* There are relatively few trials indicating a yield decline in response to soil P levels above sufficiency thresholds. However, it represents both an economic inefficiency and a potential environmental hazard.
- *Links between P application practices and environmental loss:* The major pathway for P loss is via sediment loss (P is bound tightly to charged soil surfaces). Regionally, the potential for loss varies depending on the degree of soil P enrichment, topography, rainfall, soil characteristics and grower management practices (e.g. cultivation intensity, residue management, winter crops).
- *Regulatory focus:* While mitigating P losses is seen as a good management practice it is not always a regulatory focus. For example, in some regions nutrient limits are being imposed to reduce N losses rather than P. This reflects existing N and P concentrations in surface waterways, and which of these two nutrients is most limiting to eutrophication processes. There is a body of literature available on good management practices to reduce and/or contain overland soil loses.

Knowledge frontier and gaps: vegetables, P fertiliser

- *Soil sufficiency thresholds:* The suitability of current P thresholds is often debated. Many trials have shown that a range of crops do not respond to P applications at Olsen P concentrations > 15 mg/L. Yet, established norms for these crops (especially vegetables) are much higher. Further still, many growers continue to apply P fertiliser even above these high threshold values. A comprehensive review on P sufficiency levels is needed. Identifying key grower concerns that lead to poor uptake is also vital in improving PUE in the sector.
- *Advanced delivery mechanisms:* Technologies that provide for slow release of P or help to retain P in plant available forms for longer may have uses in certain soils and production systems..
- *P leaching losses:* While moderate P enrichment is unlikely to cause major agronomic issues, it represents both an economic inefficiency and an environmental risk. To date gradual enrichment has been countered by soil management practices to reduce surface erosion and sediment loss. However, overseas there is increasing evidence of P leaching losses in P saturated soils. The tipping points and processes are not well understood for New Zealand soils.
- *High P enrichment and crop productivity:* The effect of high P availability on crop yields is not well understood. Some trials indicate an eventual yield decline at very high P levels, while others do not. Such knowledge would help to reinforce fertiliser practices that do not overload the soil with P.

Perennial fruit and vine crops

The dominant perennial tree and vine crops grown in New Zealand are kiwi fruit, apples, wine grapes, pears, stone fruit and avocado. Smaller plantings of other important fruit crops include blackcurrants and berry fruits. Key production regions include Marlborough, Bay of Plenty, Hawke's Bay and Tasman-Nelson. Perennial tree and vine production practices generally require small nutrients inputs and longer time perspectives than vegetable, arable and forage crops (years rather than weeks and months). Accordingly, there has been a much smaller emphasis on nutrient management science within the tree and vine crops sector.

Nutrient sources: Nitrogen, Phosphorus and other elements

Scientific advances in the period 1998 to 2013: perennial fruit and vines, fertilisers

The nutrient requirement of different perennial tree and vine fruit crops are at best complex and relatively specific to individual crops, and at worst, very poorly known for a large number of these crops. The larger inputs of nutrients (N, P, K, S and micronutrients) are generally associated with the establishment of new crops and these tend to be relatively low compared to many annual crops.

Experiments have shown that high N availability in many fruit and vine crops results in excessive vigour, which can increase pruning costs, reduce productivity and lower fruit and berry quality. High N availability can also affect the uptake of other nutrients (especially Ca and K) which are linked to fruit quality and storage life. As a consequence, many growers apply little or no N fertiliser to these crops. Where applied, rates are typically driven by the amount of N removed in the harvested product. There is greater use of organic N sources - especially composts which release nutrients slowly.

Some research has focussed on the use of alternative delivery mechanisms for applying fertilisers to tree crops to enhance the rate and extent of fertiliser uptake. This includes the use of foliar sprays for quick penetration and better uptake. Low dose N fertigation is also possible if a deficiency is noted. The application of these techniques tends to be driven by leaf sufficiency thresholds rather than soil based indicators of fertility to match expected crop demand.

Very little experimental work has been undertaken on P use in tree and vine crops in New Zealand. This reflects low P uptake in harvested fruits and berries. Because most orchards are grassed, surface run-off of P is not generally a major concern.

Knowledge frontier and gaps: perennial fruit and vines, fertilisers

A targeted industry driven approach is needed to identify the nutrient limitations of individual perennial tree and vine fruit crops and best management practices that avoid these limitations to ensure sustainable levels of high yielding, high quality fruit production. The specific gaps in knowledge around fertility of individual fruit crops, particularly in relation to trace elements, are beyond the scope of this review.

Forage and supplementary feed crops

Meeting the productivity targets of the pastoral industries requires the production of supplementary feed and forage crops to meet the growing demand of livestock, particularly during winter. To this end, the NZ pastoral industries have set an ambitious target of producing 45 t DM/ha/yr from supplementary feed crop systems. The industries have also set targets for substantial reductions in N leaching losses (50%) and P losses relative to baseline levels. Maximising the annual supplementary feed production on a given paddock requires the establishment of crop sequences that are based on seasonally-adapted crops with a high efficiency of light capture. However, meeting industries feed production targets will also require high inputs of water and nutrients that may increase the risk of N and P losses.

There are a wide range of crops that are grown as supplementary feed and forage for livestock consumption in New Zealand. The supplementary feed crops include grain crops (dominated by feed wheat, maize), green chop crops (e.g. whole crop barley) and conserved feeds that include crops used for silage (maize, kale) and baleage (ryegrass, cereal straw, triticale [cross between wheat and rye]) production. The nutrient management science associated with the production of these crops is broadly the same as that of other arable crops. Matching nutrient supply with crop demand is important to achieving the production targets while minimising the risk of losses (especially N).

In addition to the brought in feeds, a large proportion of supplementary feed is provided as forage crops grown as a break during pasture renewal or grown on arable farms or dedicated livestock support land. These crops are typically fed during periods of low pasture production, such as the dry summer months or during the winter. The most common forage crops grown in New Zealand include forage brassicas, fodder beet, annual ryegrass, lucerne, oats and triticale. Forage brassicas represent the largest category of grazed forage crops in New Zealand, covering an area of >250,000 ha per annum. They include kale, forage rape and swedes that are typically used as winter feed and turnips that used as summer feed.

Nutrient sources: Nitrogen & Phosphorus

The supply of N and P needed to maximise the production of forage and feed crops is fundamentally the same as that for comparable arable crops. Key points of difference in the management of N with these crops relate to maximising their dry matter production and energy content while reducing the N returns in livestock excreta. In general most N and P is supplied in synthetic fertiliser forms, though there is an increasing move towards other sources such as farm effluents.

Scientific advances in the period 1998 to 2013: forage and supplementary feed crops, N&P fertiliser

Research on supplementary feed and forage crops has focussed on:

- *Fertiliser N requirements*: the N requirements of most supplementary forage and feed crops are well known and are generally consistent with requirements of comparable arable crops. As with other crops, predicting the supply of N from mineralisation is a major limitation to accurately forecasting the fertiliser N inputs needed to meet crop demand.

- *Achieving yield potential*: The effective use of best practice nutrient (and water) management strategies with many forage crops, particularly forage brassicas, appears to be highly variable on-farm, often leading to the production of crops that are well below their yield potential. This has a significant effect on NUE and potential nutrient losses. Proprietary decision support tools such as the Forage Brassica calculator are available to assist farmers to achieve the yield potential of these crops.
- *Excess forage N*: the capacity of some crops (especially brassicas) to take up N in excess of their physiological requirements has been identified as an issue for livestock grazing. Some research has focussed on identifying management practices (especially timing of N application) that may help to reduce this luxury consumption of N and high NO_3^- concentrations in feed.
- *Production of high ME crops*: some progress has been made in identifying fertiliser x irrigation management strategies that improve the metabolisable energy (ME) of forage and feed crops but further work is needed.
- *Nutrient export*: the potential impact of whole crop removal on nutrient export from paddocks growing cut & carry crops has been identified but the range of losses and their implication of nutrient management of subsequent crops are poorly known.
- *Nutrient import*: the increased loading of nutrients to pasture soil from brought-in feed has been identified and is reasonably well known for grain and common conserved feeds.
- *The 45 t DM/ha/yr target*: The limitations to achieving the industry target for supplementary feed production have been quantified from field trial and modelling experiments. However, meeting the achievable levels of production require very high levels of irrigation and N, increasing the risk of N losses from leaching and gaseous emissions.

Knowledge frontier and gaps: forage and supplementary feed crops, N&P fertiliser

- *High energy, low N crops*: further research is needed to identify management practices that maximise the ME of high yielding supplementary feed and forage crops. A further challenge is produce these high energy crops with low N content to reduce the N returns from livestock excreta.
- *Nutrient supply from livestock excreta and effluents*: the amount and rate of nutrient release from livestock excreta following the grazing of forage crops are poorly known and needs to be included in nutrient management plans and fertiliser forecasting for subsequent crops and pastures. Similarly, the rate of nutrient release from livestock effluent applied to crops is also poorly known.
- *Closed loop nutrient management systems*: integrated nutrient management strategies that are designed to better account for nutrient trading between land used for supplementary feed production (e.g. arable farms or support blocks) and the grass platform are needed. Is there an opportunity to develop rotational farming practices that permit better harvesting of nutrient reserves and reduce need for fertiliser inputs, effectively improving nutrient recycling?

- *Achieving yield potential*: greater emphasis needs to be placed on dissemination and uptake of best practice nutrient (and water) management strategies and the use of available decision support tools to lift the overall production of forage crops. The largest gains can probably be made with crops grown as a break during pasture renewal, primarily because these farmers often lack crop management expertise.

Nutrient cycling: Nitrogen & Phosphorus
The primary issues associated with nutrient cycling in forage and feed crop systems are the trading of nutrients between farms (i.e. where they are produced and where they are used), the concentrated returns of nutrients in livestock excreta during the grazing of forage crops, the use of livestock effluents to grow crops, and the associated risks of nutrient losses and management to mitigate these losses while sustaining high levels of production.

Scientific advances in the period 1998 to 2013: forage and supplementary feed crops, N&P cycling

Research on supplementary feed and forage crops has focussed on:

- *Maximising supplementary feed production*: The limitations to achieving the industry target for supplementary feed production have been quantified from field trial and modelling experiments. However, meeting the achievable levels of production require very high levels of irrigation and N, increasing the risk of N losses from leaching and gaseous emissions.
- *Predicting soil N supply*: Rates of N mineralisation following the cultivation of long term pasture for crop production have been shown to be much higher than mineralisation rates from continuous cropping soils. This is generally considered in forecasting fertiliser N requirements of crops on mixed cropping farms but accurate predictions of the mineralisation rates are far from assured.
- *Use of effluents to grow forage crops:* There is evidence to suggest that livestock effluents can be used to successfully grow forages on nutrient-depleted cropping soils. However, there are no process-based tools to forecast the rate of nutrient supply from these organic sources (availability is much slower than synthetic fertilisers).
- *Crop cultural practices*: the direct drilling of forage crops during pasture renewal has been shown to achieve high levels of crop production while reducing nitrous oxide emissions from urine following grazing, primarily due to reduce levels of compaction from stock treading.
- *Nutrient returns from forage crop grazing*: Preliminary estimates suggest that the returns of nutrients (N and P) in livestock excreta (urine & dung) during the grazing of forage crops can be very high and may be a major source of N losses from N_2O emission and nitrate leaching and of P losses in run-off on sloping land.
- *N_2O emission from grazed forage crops*: Although the number of studies are limited, the best estimates suggest that rates of N_2O emissions from grazed forage crops (with treading and urine) are typically very high, but vary depending on soil type, extent of compaction and climatic conditions. The available data suggests that the N_2O emission factor for urine N in

forage crop systems may be higher than emission factor used for urine N inputs to pasture.

- *N cycle inhibitors*: there has been some research on the use of urease and nitrification inhibitors to reduce the risk of nitrate leaching and N_2O emissions from grazed forage crop systems. Early work seems promising but has only been applied under a narrow range of soil and environmental conditions.
- *Grazing management practices*: there is some evidence that short rotation grazing of pastures and crops may provide a means of managing the amount and location of excretal returns from livestock grazing, but further research is needed.

Knowledge frontier and gaps: forage and supplementary feed crops, N&P cycling

- *Increasing the intensity feed production*: building on previous research aimed at maximising the total per ha production of forage and feed crops, future research should focus on quantifying the intensity of feed production (DM produce per unit N applied) and identifying production systems with lower risk of nutrient losses. Establishing accepted NUE benchmarks would benefit the sector.
- *Predicting soil N supply*: Accurately estimating soil N supplying capacity remains an important barrier to forecasting the fertiliser requirement of arable, vegetable and forage crops. As in other systems, tools to improve the predictions of N mineralisation are needed to achieve this goal and to minimise the levels of mineral N in the soil profile at the end of the growing season, thereby reducing the risk of nitrate leaching.
- *Nutrient returns from forage crop grazing*: Better quantification of returns of nutrients (N and P) in livestock excreta (urine & dung) during the grazing of forage crops is needed, including the range of nutrient concentration in excreta and volume and spatial distribution of excreta returned under different grazing systems.
- *Nutrient mineralisation from residual excreta and livestock effluents*: The contribution of residual livestock excreta (following forage crop grazing) and livestock effluents to N mineralisation during the production of subsequent crops is virtually unknown but represents a potentially large source of mineral N, P and K that could support crop production and/or increase the risk of nutrient losses, especially N losses (leaching and gaseous emission) and P run-off. Understanding the factors that affect the amount and timing of this nutrient release is needed.
- *Nitrate leaching and P run-off from grazed forage crops*: Better quantification of N leaching (including NO_3 and DON) and P losses in run-off are needed from a range of forage crop systems. There is a need to understand the key factors that affect these losses as first step in identifying suitable mitigation options.
- *Crop establishment practices*: further research is needed to confirm that Direct Drilling of forage crops during pasture renewal reduces nitrous oxide emissions from urine following grazing in a wider range of soils. This research also needs to be extended to quantifying the impact of direct drill systems on nitrate leaching losses following grazing and demonstrating the

ability to reliably produce high yielding crops with these establishment practices.

- *Crop cultural practices*: in addition to direct drilling, there is a need to explore other crop cultural practices that may help to reduce the risk of N and P losses from grazed forage crop systems. This might include the retention of crop residues to assist in immobilising mineral N and the sowing of deep rooted catch crops to mop up residual nutrients from grazing of forage crops.
- *N_2O emission from grazed forage crops*: further studies of N_2O emissions from grazed forage crops (with treading and urine) are needed to verify and improve estimates of the N_2O emission factor for urine N in these systems. These studies should encompass the effects of compaction and climatic conditions on a range of relevant soils.
- *Denitrification*: The primary factors that affect denitrification are relatively well known. However, a much greater understanding of how soil physical and biochemical factors interact to effect denitrification rates and the end products is needed. There is also the need to develop relatively simple metrics that can be used to predict the ratio of N_2O to N_2 and the absolute levels of N_2O emissions from soils following grazing of forage crops. On-farm decisions support tools that assist farmers in managing these risks are important to reducing the environmental impacts of these nutrient intensive systems.
- *Volatilisation*: There appears to be very little if any data on the rates of N volatilisation from grazed forage crop system. The volatilisation of N from a cut & carry supplementary feed production system is expected be much the same as that for continuous arable crop systems.

Technology advances

Decision support systems (DSS) and models

Cichota & Snow (2009) reviewed NZ nutrient management models and categorised as 'research' or 'application'. Application can probably be further split into strategic (e.g. higher level, annual time step) and tactical (e.g. daily decisions on fertiliser or irrigation applications) tools. Financial models are also available; they are critical for sustainable nutrient management. Developments in computing technologies over the last 15 years (processors and platforms) have made computer models easily accessible to end users, as well as aiding their development by scientists and software teams.

Scientific advances in the period 1998 to 2013: DSS and models

Arable, forage and vegetable crops

Numerous process-driven models have been developed nationally in the past 10-20 years to help quantify important soil x crop interactions. Many account for the effects of climate, soil characteristics and grower management decisions on crop nutrient demand and soil nutrient availability (Cichota et al 2010; Jamieson et al 2001, 1998a, b, 1984; Jamieson & Semenov 2000; Li et al 2009b; Reid et al 2004b; Reid 2002, 1999; Reid & English 2000; Wilson et al 1995). The suggested uses of these models include: 1) interpreting complex farming systems and predict changes in nutrient dynamics, 2) guiding tactical, on-farm nutrient management decisions, and 3) informing the development of regulatory policy. The goal of these models is generally to improve the economic and environmental performance of crop production systems by better matching the availability of nutrients (i.e. nitrogen and phosphorus) with the demand of the crop. The goal is to avoid under application of fertiliser, which results in nutrient deficiency and yield loss, as well as over application fertiliser, which is economically wasteful and increases the risk of loss to the wider environment.

It is widely accepted that nutrient availability is a function of: 1) the net mineralisation of nutrients from soil organic matter, crop residues or animal excreta; 2) the nutrients supplied from exogenous fertilisers (both organic and inorganic forms) and N-fixation, 3) the nutrients lost as gaseous emissions or via leaching or runoff, and 4) crop uptake. Although all of these factors contribute to nutrient availability, their relative importance depends on the cropping enterprise (arable, vegetable or forage; irrigated vs. dryland, etc.) and they are considered with differing degrees of accuracy in the models. The most significant limitations to determining nutrient availability with these models are associated with predicting the supply (mineralisation and exchange) of nutrients from soil and the amount and form of the losses over the growing season. In several cases, industry sectors have supported the development of crop-specific decision support systems (DSS's) that utilise these underpinning plant and soil models. Growers or industry consultants have been the intended audiences for these tools, enabling them to generate paddock specific nutrient budgets. Decision support systems have now been developed for cereals (Armour et al 2002; Jamieson 1998b), maize (Li et al 2009b, 2006; Reid et al 1999), potatoes (Jamieson et al 2006; Reid et al 2011), sweet corn, tomatoes (Reid et al 2004a), carrots (Reid 2004), and numerous forage brassica species (Chakwizira et al 2011, 2012; Wilson et al 2006). These tools have a wide functionality range, with some providing fertiliser recommendations (rate x timing) for nitrogen only or for multiple nutrients simultaneously. Most of these recommendations are based on projections of crop yield (and therefore nutrient demand) and soil test values (as proxies of nutrient availability) that have been measured and/or modelled either at the start of a cropping season or throughout. Some DSS tools also estimate leaching losses (Li et al 2006, 2009b; Jamieson et al 2006), though the accuracy of these estimates is contentious.

In addition to the suggested use as tactical nutrient management tools, models are increasingly being used to help guide regulatory policy to improve water quality outcomes. In particular, the OVERSEER® model is being used by a number of regional authorities to set nutrient limits and monitor annual compliance across a farming business (as part of a farm nutrient plan). Although it is generally accepted that OVERSEER® is the best tool available for predicting long-term nitrate leaching losses from pastoral farming systems, particularly at the whole farm scale, a number of concerns have been raised about its use in complex annual cropping rotations (FAR, 2012). In particular, the use of an annual time step to predict leaching loses is debated because crop sequences vary considerably within a paddock and farming system. Also, there has been comparatively little field validation of the predictions for cropping rotations.

Fruit and vine crops

There are comparatively few models and DSS tools that address nutrient management of perennial horticultural crops. This largely reflects the fact that fertiliser use is comparatively minor in these industries. Recommendations are typically based on nutrient removal and leaf or soil sufficiency norms.

Pastoral

The scientific advances described in the preceding sections have provided the scientific understanding to enable continued development of models. Pastoral nutrient management models have been developed for a wide range of uses, including:

- Tactical decision making –fertiliser requirements, daily irrigation scheduling
- Strategic – whole farm models for nutrient management, not designed for daily tactical management decisions
- Research – detailed process-based models for research investigations or for identifying knowledge gaps
- Catchment-scale – scaling up to understand effects at the catchment level
- Groundwater – modelling transport and fate of nutrients from soil surface layers to receiving water bodies
- Economic – at a range of scales for assessing cost-effectiveness of management decisions, for example

The types of modelling approaches have been varied and have been matched to the purpose of the model, be it decision support or research applications. Increasingly, models have been used to assess the implications of research results; for example scaling research findings to a farm or catchment level or adding an economic analysis as an important component of sustainability. OVERSEER® is an important tool for the pastoral sector. It is an effective route to move science into the farm. However, it needs further validation and testing.

Forestry

There are two major nutrient management tools for New Zealand's planted forests. The first is FertMan, a module of the nationally available and used Forecaster™ forest management tool, and the second is NuBalm – a nutrient balance model developed for P. radiata. FertMan enables foresters to identify and quantify crop nutrient status and determine appropriate fertiliser application rates and the expected biological and economic returns. It is spatially based, producing maps of expected change in forest productivity and profitability. The focus is predominantly on N and P with less robust models for K, Mg and B. It only handles *P. radiata* currently.

NuBalm allows modelling of nutrient supply and demand for *P. radiata* both within crop rotations and over multiple rotations. It models crop growth and changes in nutrient pools over time so can be used both to analyse nutrient needs but also losses from the system through leaching. It is mainly used strategically to develop nutrient management scenarios and to analyse long term sustainability issues.

Knowledge frontiers and gaps: DSS and models

This analysis does not provide a comprehensive stocktake of available models, as other projects are doing this (e.g. Framework for Interoperable Freshwater Models: https://secure.niwa.co.nz/teamwork/display/IFM and www.onefarm.ac.nz/) . The advancements in modelling have been such that nutrient management is underpinned by a suite of models, widely used by groups ranging from policy through to farmers/consultants. Models are a good way of integrating scientific understanding and models will continue to evolve as scientific understanding improves. Because of this, models represent close to the frontiers of our knowledge in nutrient management science; and because of this they will always need more data for validation, testing and gaining user confidence. For example, even though OVERSEER® is widely used (particularly by the dairy sector), further validation is required:

- A recent review of the OVERSEER® cropping model (FAR, 2012) found that the detailed research model on which it is based has only been tested on one site. Furthermore, the modified version of the base science model, has not been validated at all.
- The OVERSEER® Pastoral model has been field validated on a number of well defined, but narrow range of sites/soils, and it is accepted that further validation is required in other situations (e.g. on stony soils as in Canterbury and Otago).
- Related to the above there is an urgent need for a comprehensive ‘sensitivity analysis’ of OVERSEER® to be undertaken,

Despite the potential benefits associated with DSS’s their current use by industry is still comparatively low. In a few cases, the tools are being used to guide tactical nutrient management decisions or are being used in abbreviated forms (for example, making generic recommendations for several similar paddocks). In other cases, the principles behind the tools (e.g. matching nutrient supply to crop demand, splitting applications to reduce risks associated with leaching) have been incorporated into cropping enterprises rather than the DSS tool itself. The constraints to direct grower use are commonly listed as cost (related to the time and expense of soil sampling and analyses to initialise the DSSs), tool complexity and in some cases concerns over the accuracy of predictions. Accuracy issues tend to be related to 1) an incomplete understanding of underlying soil processes (e.g. mineralisation of soil organic matter, soil water storage and drainage dynamics), 2) the use of average climate data rather than real time data, 3) over-simplification of the tools and inputs (e.g. generic soil descriptions) to encourage greater adoption, and 4) incorrect use of the tool by end users.

Gaps in models will be addressed by closing gaps in scientific understanding, and these gaps have been highlighted in preceding sections. However, there are also gaps relating to use of models: particularly around understanding models, their use and their limitations, so that they are applied correctly by the user under circumstances for which the model was designed.

In some cases the solutions to these challenges requires new underpinning knowledge or improved tool functionalities, whereas in others additional dissemination and training packages are required. Future DSS’s may also need to address broader management considerations (e.g. crop residues, organic amendments, tillage practices, soil structural condition, spatial variability) and their interactions with nutrient supply and demand dynamics.

Precision agriculture

Precision agriculture is enabled by new technologies (GPS, sensors and GIS) and aims to modify inputs (e.g. fertiliser, irrigation, dairy effluent, seed rate) spatially and temporally at the sub-paddock scale for cost efficiencies, and productivity and environmental gains. The accessibility of these technologies enabled precision agriculture to emerge as a research discipline in New Zealand in the 1990s, and precision practices are now integrated into a handful of New Zealand farms, with commercial precision agriculture companies being formed. Prior to this time, researchers had noted soil variability (e.g. Webb et al., 2000) and discussed the need for differential inputs, e.g. fertiliser application to hill country (Gillingham et al., 2008). However, it was the affordability of the GPS and sensor technologies that advanced our ability to measure and monitor the variability to tailor inputs to site-specific conditions in the landscape.

Scientific advances in the period 1998 to 2013: precision agriculture

Early studies scoping the potential application of precision farming in New Zealand showed that inputs such as nitrogen fertiliser should be altered to best suit the agronomic requirements of the particular crop, and land and soil conditions. Variable rate nitrogen fertiliser trials indicated that the above-average yielding parts of paddocks had scope to respond to additional nitrogen. Building on from that:

- *Electromagnetic soil surveys and prescription maps for varying fertiliser and irrigation input* - Electromagnetic sensor surveys quantify soil variability, and are used to produce maps which define soil management zones. The maps are used to target positions for soil sampling and develop prescription maps. The prescription maps are the decision support tool for variable rate fertiliser and/or irrigation placement.
- *Assessing variable rate application technologies (VRAT) for aerial fertiliser application to hill country farms* - benefits from automating fertiliser flow control from topdressing planes to vary application rates based on the potential outputs of the farmland.
- *VRAT technologies for ground-spreading fertiliser vehicles assessed* - Inaccurate application of nutrients from ground based fertiliser spreading vehicles can lead to major agronomic and economic losses (Lawrence et al., 2005: Lawrence, 2007). A range of variable rate fertiliser applicators are now available in New Zealand.
- *Assessing variable crop response using optical sensors for improved strategic N input management* - Measurement of canopy reflectance with crop sensors has the potential to use the plant as an indicator of N requirements. A number of optical sensors are now available to farmers to actively monitor the development of growing crops such as cereals, brassica, maize and ryegrass.
- *Pasture yield mapping* - Pasture yield mapping also provides valuable information for strategic variable N input decisions in pastoral agriculture. Hyperspectral sensors are also being tested in the field to estimate pasture yield and quality.
- *Assessing pasture quality to assist nutrient management, using unmanned aerial vehicles (UAVs)* - Airborne sensors mounted on unmanned aerial vehicles (UAV) offer a number of advantages over other remote sensing methods that are limited by temporal and spatial resolution, and proximal sensing methods which can be laborious when surveying a whole farm (e.g. Fig. 8). Initial trials have been conducted
- *Animal tracking for improved nutrient management* - Methodologies are being developed to observe, track and analyse the behaviour of dairy cows managed on pasture under commercial conditions. This may lead to better

nutrient management through better understanding of the distribution of nutrient deposition via excreta.

Knowledge frontiers and gaps: precision agriculture

Precision farming research advances in New Zealand over the last fifteen years have identified a number of methods and applications which can provide significant benefit to assist on-farm nutrient management. Initial studies investigated the potential productivity gains with application of variable rate technologies to nutrient management. They also identified that although the benefits were there to be taken, the industry lacked adequate variable control application equipment; and this is now being addressed. New tractors now have accurate GPS installed, and variable rate fertiliser applicators are available. A variable rate modification has been developed for sprinkler irrigation systems to provide precision placement of irrigation water with individual sprinkler control (www.precisionirrigation.co.nz), and this is now marketed internationally. Commercial precision agriculture companies are starting to emerge (e.g. Agri-Optics www.agrioptics.co.nz; Precision Irrigation NZ-Lindsay Corporation). These companies provide commercial crop scanning, EM mapping, GPS farm boundary mapping and precision irrigation systems.

Irrigation (fertigation)

Irrigation water provides the diluent for direct application of nutrients, e.g. dissolved in the irrigation water, or after solid fertiliser application to the land. Also, dairy farm effluent may be spread or "irrigated" onto paddocks to recycle nutrients. The advent of variable rate irrigation systems allows the equipment to apply water with nutrients and other chemicals to meet the specific needs of crops in unique zones. King et al. (1996) investigated the use of centre pivot irrigation systems for spatially variable application of nitrogen, and showed that spatially varied N application was achieved at the same accuracy as that of conventional uniform applications.

Scientific advances in the period 1998 to 2013: Irrigation (fertigation)

- *Fertigation* – this applies nutrients in irrigation water to plants and has evolved with the progression of irrigation technology. Fertigation by sprinkler irrigation systems is a relatively new development, and these irrigators are able to apply a uniform rate of fertiliser and chemicals to crops over areas typically 50 - 100 ha under a single irrigator. They can also apply variable rates of nutrients, where the irrigator is modified with variable rate control. As well as developing fertigation the focus has been on methods to deliver the nutrient solution:
    - *Drip irrigation* is the most efficient method to deliver water and nutrients to a plant, but is not always practicable (e.g. in cultivated soils), is expensive to install, and requires regular maintenance,
    - *Subsurface drip irrigation* of pastures has been trialled in Australia, when freshwater was at an unprecedented shortage (Finger et al., 2007). It appears likely that this highly efficient method of introducing nitrogen fertiliser to the root zone will militate against nitrate leaching losses and nitrous oxide emissions in a well-managed system, but issues of acidification will need to be further investigated

  - *Centre pivot fertigation* is a relatively recent development and is suited to irrigating larger areas with less labour than other types of irrigation (Werner, 2000). There are a handful of early adopters in New Zealand, and the technology is showing a steady rate of uptake in other parts of the world.
- *Farm dairy effluent (FDE)* – research has derived the most appropriate method for land application of FDE:
  - *Application* - Small, self-propelled travelling irrigators are commonly used to apply FDE to land in New Zealand. These irrigators are low maintenance and have a range of operating speeds and hence ability to apply effluent at a variety of depths (Heatley, 1996).
  - *Scheduling* - Deferred irrigation delays irrigating very wet soils until a specified soil moisture deficit is reached (Houlbrooke et al. 2004b). FDE is then irrigated at an amount less than the soil moisture deficit to avoid drainage and runoff losses which are more likely to occur as the soils becomes wetter than field capacity.

Knowledge frontiers and gaps: Irrigation (fertigation)

The principle that fertigation can improve nutrient use efficiency is well established. However, there has been very little uptake of fertigation practices in New Zealand to date, but with Variable Rate Irrigators and drip systems receiving new and renewed attention, and regulatory demands for improved fertiliser use efficiency, it seems likely that fertigation practices will increase in the future.

There is potential for much greater spatial optimisation of nutrient management, using targeted application to ensure that nutrient inputs such as FDE are not placed in critical source areas of nutrient loss, or that applications are placed according to plant needs (Monaghan et al., 2007). The automation of FDE scheduling and application, using real-time daily weather records and computer simulation models or sensors that track storage pond volumes and soil moisture deficits to identify opportunities for irrigation, is also likely. A Global Positioning System (GPS) irrigator could identify its position in the landscape and customise applications to reflect soil chemical and physical characteristics. The automation of FDE management systems offers advantages in terms of reduced farm labour requirements and fewer opportunities for operator error. Technologies that reduce the volumes of FDE produced at the milking shed, such as covered yard holding areas that do not require daily wash-down, are also likely to greatly reduce the frequency of unwanted discharges of FDE from soil to water. While these systems may not currently appear economically attractive, with the likelihood of increased regulation impinging on farm nutrient management, such complex systems allow nutrient inputs to pastures to be placed with precision, according to need and in a manner that poses less risk of runoff to waterways (Monaghan et al., 2007).

Soil Process inhibitors

Process inhibitors are seen as a way of temporarily blocking nitrogen transformations which, in some circumstances, can then decrease losses. For pastoral systems, this has been mainly:

- Nitrification inhibitors, primarily dicyandiamide (DCD) – decreases N_2O emissions and NO_3 leaching losses

- Urease inhibitors, primarily N-(n-butyl) thiophosphoric triamide (nBPT) – decreases NH_3 emissions

Although the principles of process inhibitors have been understood for many years, their application at the farm scale is a relatively new technology.

Scientific advances in the period 1998 to 2013: soil process inhibitors

Nitrification inhibitors

This has focused almost solely on DCD and on urine given that urine is a major source of N_2O and NO_3 loss. About two thirds of research has been directed at the urine patch level, and about one third at paddock-scale effects. Paddock scale effects have focused on N leaching and pasture response. Scientific advancement has focused on:

- *Quantifying effectiveness*: in decreasing losses of NO_3 and N_2O, and the factors that affect efficacy
- *Application technology*: formulations, rates and frequencies
- *Productivity gains*: i.e. whether extra pasture growth results from saved N
- *Winter forage crops*: although most understanding is with grazed pasture, research is also being done with grazed forage crops
- *Modelling*: the need to scale up effectiveness from individual urine patches to paddock and farm; and to also extend estimates of effectiveness to conditions that have not been tested experimentally

The value of these data when assembled into a body of work is: to be able identify the main drivers of effectiveness (for further investigation); to construct empirical models based on the data; and to use for validation of, for example, independently derived, process-based models.

Urease inhibitors

The focus to date has been the use of urease inhibitors with urea fertiliser rather than urine. Scientific advancement has focused on:

- *Quantifying effectiveness*: in decreasing NH_3 losses and the factors that affect efficacy
- *Application technology*: formulations and rates
- *Productivity gains*: increases in pasture yield

Knowledge frontiers and gaps: soil process inhibitors

Process inhibitors are researched world-wide. Our scientific advancements are about understanding their behaviour and application in NZ conditions; though it could be argued we are a world leader applying nitrification inhibitors directly to soils.

Until the recent embargo on DCD, nitrification inhibitors were used on some farms and in experimental future farming systems as a technology for improving nutrient use efficiency. Further knowledge is required for improved effectiveness.

There has been limited work on DCD targeted at the urine patch to improve efficiency of use, only limited work on long-term effectiveness and little work on feedback effects or benefits in legume-based systems.

There is a gap in understanding efficacy under a wide range of circumstances; mainly because much of the development work has been centred on 3 locations. Therefore, we do not have the necessary research information to quantify the cost and benefits of DCD in any given farm situation. Research is also required to predict when it should be applied Much of the understanding is at the urine patch scale and this needs to be scaled to paddock and farm to be able to provide estimates of effectiveness; both in terms of mitigating losses and estimating productivity effects.

Here, modelling plays a key role; for both extrapolating to other sites and for scaling from patch to paddock. The ability to model DCD is improving but needs further development, i.e. being able to model its decay and hence effectiveness over time. More knowledge is required regarding use of inhibitors in winter-grazed forage crops. This is a relatively new area. Further work on its environmental fate is also required.

A urease inhibitor is available for on-farm application in a commercially available urea fertiliser formulation. Currently, urease inhibitors are not targeted at urine patches or during effluent manure storage and application. Although decreasing these losses may improve nutrient use efficiency, there has been no driver to limit NH_3 losses.

Wetlands

Wetlands range from completely natural landscape features to engineered structures, but all work on treating intercepted water to remove contaminants (nitrogen, phosphorus, sediment and pathogens). 'Treatment' occurs through a number of physical, chemical and biological processes that can be enhanced by design features within the wetland (such as placement of P sorbing material). The filtering functions of wetlands and their ability to remove sediments and pollutants from water passing through them are well known. Constructed wetlands, for the treatment of wastewaters or drainage from paddocks, are designed to use processes that occur in natural wetlands.

Additionally, filters (generally P- sorbing materials) have been used in the landscape to intercept surface runoff or drain flow.

Scientific advances in the period 1998 to 2013: wetlands

- *Efficacy of wetlands* – their effectiveness in removing pollutants (N, P, SS and faecal organisms)
- *Design of wetlands* – fit with the landscape, for example.
- *Enhancing efficacy of wetlands* – by adding structures to slow flow through and/or adding filter materials (e.g. Allophane, Papakai tephra, limestone and alum have been judged as materials with the most potential to adsorb and retain P). There is, however, some concern that these types of initiatives of dosing to retain P are short lived and therefore temporary methods to allow other techniques to be put in place.
- Other approaches a number of other landscape features have been investigated, including:

- o Drain filters - use some sort of filter material to trap P before it enters waterways. Materials trialled in NZ include steel slag (loose or in "P – socks"), tephra, allophane, alum, coal fly-ash, limestone, slag, seashells, shell-sand and tree bark.
- o P sorbing socks – as above but placed at points in the landscape to intercept surface flow.
- o Denitrification walls – use of a C-rich substrate such as sawdust in a channel to intercept lateral flow of water to decrease its N content via denitrification.

Knowledge frontiers and gaps: wetlands

That wetlands can be reasonably effective for mitigating some losses in some situations is well known, with published ranges of effectiveness by pollutant and by wetland type. The gaps are more likely around implementation and placement on the farm or catchment.

Further work is required to understand the best role for 'P-socks' (effectiveness, how they should best operate to intercept runoff). One of the issues is availability of material (best if the material can be sourced locally). Similarly, denitrification walls appear to be an under-used approach at the moment.

DISCUSSION

Knowledge frontiers

Analysis of pastoral systems

Pastoral systems aim to produce feed as efficiently as possible and then for the animal to convert to product as efficiently as possible. Nutrient not used in product or retained by the animal is excreted for recycling. Nutrient management science in these systems is about understanding:

- the science of individual nutrient cycling processes
- the interactions between processes
- the effects of management interventions on processes and their interaction
- the net effects on nutrient cycling at the farm-scale

We have a good understanding of the N and P nutrient cycles; and we have a good understanding of where they leak. The challenge is managing these cycles at the farm level and beyond and finding solutions, some of which may be implemented at the farm levels, others by more direct intervention (nutrient capture within water ways for example or controlled release N fertilisers). This, in a nutshell, is the challenge for nutrient management science; to develop the understanding of the science at the farm scale to aid management decisions.

Furthermore, NMS informs the development of sustainable farm systems, balancing productivity, profitability and footprint. Thus, at some stage in the development of farm interventions there also has to be a cost benefit analysis of those intervention(s).

In short, nutrient management science has been about, and will continue to be about developing best practice, and operating and thinking in the whole-farm environment.

Dairy systems

Scientific advancement has provided a good understanding of nutrient cycling through dairy production systems. Many of the recent scientific advancements have been around developing management interventions to decrease nutrient losses (and, by inference, improve nutrient use efficiency). This research is on-going. Because of the need to understand consequences at the farm level for profitability and footprint, models are an essential part of developing and testing the scientific understanding. This ranges from application models (e.g. OVERSEER®) to research models (e.g. APSIM) to financial models (e.g. Farmax).

There has been considerable advancement in measuring, understanding and modelling N and P flows though dairy production systems and the development of management practices to improve nutrient use efficiency. There are multiple points of intervention, targeting feed, soil, animal, and excreta.

Scientific understanding needs to continue to grow to fill gaps in our knowledge of processes and management, as detailed in earlier sections. Development of new interventions to improve N use efficiency needs to continue. The challenge is assessing these impacts at the farm-scale since most research is undertaken at the sub-paddock level. Even for experiments at the management block level, this requires extrapolation to the farm when that farm is an amalgamation of management blocks and structures (effluent system, milking parlour, feed pads etc.).

Features of dairy production systems that tend to differ from dry stock enterprises with implications for nutrient management include:

- Effluent management systems – important sources of nutrients and can replace some fertiliser applications
- Urine/dung – as with dry stock systems, these drive much of the nutrient cycling but differ in nutrient concentrations and loads
- Feed sources – increasingly, in some production systems there is a reliance on significant external inputs of forage and non-forage feeds. Fertiliser inputs - generally more N use in dairy systems than most dry stock systems, with often less reliance on clover N fixation

Dry stock systems

While there has been scientific advancement in the understanding of nutrient cycling in isolated/discrete parts of these systems, the challenge of nutrient management science for these enterprises is generally exacerbated by the size of the properties compared with dairy farms (often several 000 ha). Dry stock farms often consist of a wide range of land use classes and managing system nutrient inputs and losses at this scale is daunting.

Traditionally the dry stock systems have relied solely on legumes for N supply for maintaining and/or increasing pasture production. There is good scientific information available to manage P, K and S inputs and this is available in a proprietary econometric model owned by FANZ so that farmers can be better informed about their farm nutrient program and fertiliser advice. This model is due to be updated. Use of N fertiliser tends to be tactical to fill short term deficits in pasture supply in late winter/early spring or to manage an autumn feed deficit to enable wintering of capital stock. The science which has informed nutrient cycling in dairy systems can provide good information for nutrient management in the dry stock sector as well and basic principles of nutrient cycling in the dairy sector can inform models for nutrient cycling for a dry stock systems although some cautions will apply.

To date there has been less regulatory and public pressure on controlling/minimising nutrient losses from dry stock farms compared to more intensively managed land uses (dairy and cropping/horticulture). Attention has focussed on the more intensively managed dairy sector. Some dry stock farms manage large areas of their land as intensively as dairy farms, with relatively high inputs of N and P and subsequently large amounts of urine and dung deposited on these areas. Other dry stock farms have every little land suitable for intensive management. Generalisation within this sector can problematic as the dry stock sector encompasses a diverse range of farm systems.

Recent advances in understanding soil characteristics and land use capabilities of the different land classes which make up a dry stock farm have encouraged increased farmer awareness of matching to management practices so as to optimise production and minimise nutrient loss. This has been driven by the need to minimise management impacts on soil physical structure and function and soil erosion. Emphasis has not primarily been on nutrient loss/NUE, although this is seen to be of increasing importance, especially for P and carbon (C). Whilst there is some small plot or paddock-scale information on the impact of dry stock on nutrient cycling, there is little information on nutrient cycling at a farm system level, particularly in topographically diverse landscapes. Application models such as the feed planning tool ‘Farmax’ play an important role in providing farm managers with a range of options for optimising whole farm production and financial performance.

Challenges relate to identifying grazing/farm management practices which minimise N, P and C loss to air and water and specifically targeting key times of year when systems are most vulnerable to nutrient loss. To this end, research on the impact of winter/early spring management of pastures and forage crops on vulnerable soils and/or on challenging topography is needed. This will assist in informing system design of profitable dry stock systems which minimise P, N and C loss to air and water, and hence increase NUE.

Analysis of forestry systems

Research on NMS in forestry first focussed on the ability to grow crops on very nutrient deficient soils, and results from this research this has led to the overall improvement of the nutritional status of the planted forest estate as fertiliser has been applied to remove those deficiencies. Fertiliser use has decreased now that soil fertility levels have been improved. However the sector now faces new challenges which relate more to increasing unit productivity and economic returns from the forests.

The NZ Forest Owners Association has a goal of doubling per hectare forest productivity by 2025[1] and NMS will need to play a major role in achieving this goal.

[1] http://www.nzfoa.org.nz/file-libraries-a-resources/cat_view/77-research-science-a-technology

Smart approaches will need to be explored to enable effective use of nutrients – increasing regulation will make it more difficult to apply fertilisers, so biotechnology approaches both in the crop and in the soil need to be explored. Investigation of biological N fixation with understory legumes, the manipulation of soil microbial and myccorhizal systems to enhance nutrient uptake and the development of tree genotypes with higher productivity but also greater nutrient use efficiency will be major challenges.

Where fertiliser or soil amendment (such as biosolids) are an option, research to increase the certainty of response, especially to Nitrogen, but to a lesser extent P and other elements will be needed. While fertiliser requirements have traditionally been determined through foliar nutrient status, soil testing is likely to provide a better assay. A better understanding of N and P cycling and the organic pools of nutrients will be very important for developing new soil tests.

As tree crops are long term, the ability to predict and model the effects of NMS on crop productivity, economic returns, and environmental effects will be very important and these models will be required to be site specific, and also to be able to account for climate change effects.

Analysis of cropping systems

The general aim of most crop production systems is to maximise both the yield and quality of harvestable crop products through profitable use of nutrient inputs and minimal losses to the wider environment. The primary challenges for nutrient management science in cropping systems include:

Predicting crop nutrient demand and delivering crops with specific nutritional characteristics: For many crops we have a fairly good understanding of the nutrient requirements of different crops though this can vary substantially depending on dynamic conditions that affect productivity (e.g. seasonal weather, cultivar selection, farmer management decisions, irrigation, pests, diseases and weeds). Improving the ability to more accurately forecast crop nutrient demand (ideally in real time) is therefore central to increasing overall nutrient use efficiency. There is also an opportunity to manipulate nutrient availability in order to deliver crops with specific nutritional characteristics (e.g. lower N concentrations in bread wheat or forage brassica).

Predicting nutrient supply from soils: An on-going challenge across annual crop production systems remains accurate prediction of the amount and rate of nutrients supplied by the soil (especially nutrients supplied by mineralisation of soil organic matter or fixation processes). The absence of effective soil tests and tools to make real-time predictions of N mineralisation over a growing season(s) is a major barrier to improving fertiliser N forecasting and mitigating the risk on N losses to the environment. These predictions are heavily influenced by inherent soil properties, environmental factors and land use management trends, factors that can exhibit strong temporal and spatial patterns. As a result, it can be difficult to consistently apply the right amount of nutrient, at the right time and in the right place. In some cases nutrient form is also central to nutrient use efficiency - not only for yield outcomes, but also for product quality.

Developing whole-of-farm tools and management practices that growers can adopt: New whole-of-farm tools and management practices that combine improved predictions of crop nutrient demand and soil nutrient supply patterns are essential in delivering further efficiency gains across the arable, vegetable, forage and horticultural sectors. An ability to seamlessly integrate nutrient management across crop and livestock systems will also become increasingly important as closer linkages are expected between these sectors.

Identify appropriate benchmarking data for comparative purposes: There is a shortage of reliable benchmarking data that can be used to evaluate nutrient use efficiency across a variety of production systems. Such data is useful for assessing both the performance of current production practices as well as those being proposed for the future. It is also central in assessing the adoption of proven practices by different sector groups.

Predicting and mitigating nutrient losses: Our ability to predict leaching, surface and gaseous nutrient losses is also incomplete, as is the suite of management packages that can be used to mitigate such losses.

Nutrient intensive forage and feed crops systems: Meeting the productivity targets of the pastoral industries will require increased production of supplementary forage and feed crops to meet the growing demand of livestock. There are significant challenges in meeting these productivity targets while reducing the losses of nutrients to the wider environment. There is need to focus on improving agronomic practices to meet the yield potential and increase the metabolisable energy and nutrient use efficiency of crops. There is also a need to develop management practices and technologies that reduce and recycle the large quantities of nutrients (especially N) returned in animal excreta and mitigate the risk of losses through leaching and gaseous emissions.

NUTRIENT MANAGEMENT SCIENCE – USE AND UPTAKE

REVIEW METHODS

Given the constraints of time and resources the review was limited to 35 key stakeholders whom we considered had a good national overview of the topic area and of the sectors (arable, dairy, horticulture, forestry, and sheep and beef). Stakeholders were drawn from industry associations, farmers, policy makers, fertiliser company representatives, consultants, foresters, orchardists, regional government and soil scientists.

We used a semi structured interview and questionnaire approach to gather information for subsequent synthesis by the project team. The interviews covered the following key topics: main sectoral issues in NMS, current NMS practice, information sources, science knowledge and tool awareness and usage, and effectiveness of NMS knowledge implementation.

Individual phone interviews were undertaken with 27 of the 35 stakeholders. It was not possible to interview the other 8due to availability issues so these were sent a link to an online survey, using SurveyMonkey™, to get full coverage of the group. Those interviewed were also sent an online link with four follow-up questions, allowing for quantitative analysis of the relative importance of soil processes, awareness and usage of specific sources of information, and awareness and use of tools.

Interviews were transcribed and the findings distilled by the project team to provide perspectives on the key questions. The online survey results were also synthesised and summarised. These findings are presented by sector, and an overall set of conclusions on use and uptake of nutrient management science developed.

FINDINGS

A. INTERVIEW/SURVEY FINDINGS

Current practice, key issues, and Nutrient Management knowledge needs

Levels of nutrient use vary across sectors, with forestry potentially being the lowest and dairy the highest. There is however a degree of commonality in the reported issues, with nutrient (mainly N) impacts on the environment and the likely increase in regulation of nutrient use being of concern to varying degrees across all sectors.

Sector	Current practice	Key Issues	Knowledge needs
Arable	Science perceived to be struggling to keep up with top producers' practice	Nitrogen impacts on the environment. Regulation of N use and 'right to farm' Balancing increased productivity and environmental impacts Lack of robust and easy to use management tools	Better understanding of soil N processes (leaching, mineralisation) Knowledge requirements for farm plans
Dairy	High level of nutrient inputs	Compliance with new regulations Balancing increased production with regulatory requirements Nutrient budgets a new concept and can be confusing	Better tools to balance productivity, economics and environmental impacts
Forestry	Low level of nutrient inputs overall Use of nutrients in nurseries Fertiliser application at crop establishment Crop monitoring, correction of deficiencies in first 10 years	Environmental impacts of N application Matching N supply with demand Impacts of high N on wood quality Predictability of N responses	Nutrient status diagnostics Economic benefits of fertiliser application Efficacy of different P sources
Horticulture	Use and needs varies across the wide range of crops grown Focus on balancing input needs with crop demands	Increasing scrutiny of nutrient inputs (vegetable growers especially) Concern about increasing regulation Lack of confidence in decision support tools	Improved understanding of fertilisers and what happens to them once applied Improved fertiliser recommendations
Sheep and beef	Input levels relatively low	Phosphate run off and erosion impacts New concept of nutrient budgets	Understanding the value proposition of using new scientific findings

Table 1. Current NMS practices, issues and needs by sector

Soil processes are important for nutrient management, and the level of importance accorded the processes varied across sectors. Soil microbial processes, leaching, and effluent impacts were the three most important processes for arable, horticultural and pastoral systems, while forestry differed with topsoil erosion the most important process followed by effluent impacts and loss of N gases (Table 2).

On a scale of 1 (low) to 10 (high), please indicate the importance of the following aspects in managing nutrients in a stand/crop/pasture?			
	Average Responses		
	Forestry	**Pastoral**	**Horticultural/ arable**
Leaching		10	9
Weathering	3	2	2
Microbial activity		8	7.5
Loss of N gases	6	5	6
N fixation	2	9	5
Immobilisation		7	4
Effluent impacts	8	6	6
Topsoil erosion	9	3	3

Table 2. Relative importance of soil processes by sector

The need for increased understanding of nutrition management across all sectors was apparent. The specific needs varied across sectors. An overarching common theme was the need to better understand the interactions of nutrients with crop productivity, environmental impacts and economic returns. Overall improved understanding of soil processes was frequently mentioned.

Sources of NMS information

Sector	Information sources	Comments
Arable	Foundation for Arable Research (FAR) material Fertiliser representatives Consultants Landwise conference 'Looking over the fence'	Heavy dependence on intermediaries, a few farmers use tools themselves Looking for trusted advisers Looking for translation of science into easy to understand language and rules of thumb
Dairy	Agricultural consultants Contractors Vets Software tools	Heavy dependence on intermediaries, a few farmers use tools themselves Looking for trusted advisers Looking for translation of science in to easy to understand language and rules of thumb
Forestry	Testing laboratory recommendations Forest health advisors CRI scientists Colleagues Fertiliser representatives Research consortium Future Forests Research (FFR) Software systems Own experience	Many forestry managers experienced in nutrition management Development of best practices a slow iterative process between managers and fertiliser reps Less cooperative research and development across companies than in past Links to scientists diminished
Horticulture	Specialised fertiliser representatives Consultants Sourced own information	Limited NMS resources available, variable across crops Depend on a small pool of consultants Consultants report a lack of specific NMS information
Sheep and Beef	Agricultural consultants Contractors Vets Software tools	Heavy dependence on intermediaries, a few farmers use tools themselves Looking for trusted advisers Looking for translation of science into easy to understand language and rules of thumb

Table 3. Sources of Nutrient Management Science Information

From these interviews and from known research reports[2] it became clear that all sectors depend heavily upon intermediaries like agricultural consultants, contractors and veterinarians for their scientific information. They need and want people they trust to interpret science information for them and translate it into easy to understand language and rules of thumb. Fertiliser company representatives are a very common source of information for them and these representatives also tend to use the tools that come from NM science.

A common view appears to be that information is patchy both across and within sectors, and that the form of the information may not be ideal, being overly complex and hard to use. Additionally information availability can be poor due to shortages of experienced advisers.

Calculators, OVERSEER®, and soil test results were found to be the most commonly used of the listed sources, followed by fertiliser representatives and CRI scientists (Table 4).

[2] For example, *Botha, N., Parminter, T, and Bewsell, D. 2008. Learning from success: Adoption of Nutrient Budgeting at Rerewhakaaitu and Toenepi. June 2008.*

Which of the following sources of information have you used in the past year? (Check all that apply)					
	Response Percent	Forestry	Pastoral	Horticultural /Arable	Reasons for use
DESC	0%				
Best Management Practice guidelines	10%				
Overseer	70%		✓	✓	Preparing fert budgets; Estimating N loss; Scenarios
FarmID	10%		✓		ID a farm
NuBALM	0%				
Calculators	80%	✓	✓	✓	Preparing fertiliser budget; Prediciting yields
Forecaster	20%	✓			Predicting yields
Field Guides	20%	✓			Identifying deficiencies and disease
VSA tools	20%				
Fertiliser rep	60%		✓	✓	Advice/ discussion; soil sampling
Field Advisor	30%		✓		Advice
CRI Scientist	60%	✓	✓	✓	Advice/ discussion/ brainstorm
Laboratory testing	70%	✓	✓		Soil tests; herbage; Foliage analysis
					Key: ✓ = med use ✓ = high use

Table 4. Usage of key sources of information by sector

Use of Nutrient Management science knowledge and tools

Awareness and usage of tools

Overall awareness of tools is good to high, but usage is not. This suggests a problem in the technology transfer chain and/or the relevance of current tools, which are areas of focus for improvement in nutrient management. In some cases tools are being applied beyond their originally intended purpose in the absence of a suitable alternative.

Sector	Awareness	Usage	Comments
Arable	Good awareness of currently available tools e.g. wheat calculator, FAR information sheets, field days	Low by farmers themselves, reliance on advisors Soil sampling and analysis, including deep N widely used	Tools commonly used by researchers to increase understanding of systems Deep N use decreasing due to cost Consultants using some components of tools or adapting to use outside original design – suggests gap Availability of tools and associated extension has led to capacity development within sector Concern around accuracy of OVERSEER® for arable sector
Dairy	Good awareness of currently available tools e.g. OVERSEER®, RPM from DairyPush, Feed budgeting	Most farmers would rely on advisors to use tools for them (especially OVERSEER®), though some farmers	Mismatch between recommendations from tools/advisors and on farm action. Range of suggested reasons for this, e.g.

		will use RPM and feed budgeting tools, and riparian strip and contour tools to lower P levels. Most will now have nutrient budgets	lack of trust in tools/advisors, level of understanding of advice by farmers, and shortage of experienced advisors
Forestry	Good awareness across the corporate sector but less so in farm forestry circles Main tools: Forecaster™, forestry calculators and laboratory fertiliser recommendation schemes Lower awareness of developments in fertiliser technologies	90% of corporate forestry uses laboratory foliar testing and recommendation services Prediction of yield improvement from fertiliser normally undertaken in house using Forecaster™ by experienced forest managers	Increased awareness of forestry tools within the farming sector would be beneficial for small forest owners Corporates looking for more site specificity in tools and better treatment of economics and log grade changes after fertilisation
Horticulture	Generally aware of tools available, high awareness of soil testing	Usage overall is low due to gaps in information and wide range of crops and systems	Lack of information an issue. Lack of confidence reported in the tools, especially where the recommendation is not to fertilise OVERSEER® cannot deal with complex horticulture systems Some tools being used for other than their intended aim[3]
Sheep and beef	Moderate and increasing awareness of currently available tools e.g OVERSEER®, Rising Plate Meter (RPM), LEPT	10-15% of farmers will use tools such as RPM, feed budgeting and LEPT themselves Majority of tool use will be by advisors	Increasing awareness is likely driven by increasing regulatory compliance needs. Overall uptake and use of advice from tools low Low level of confidence in tools

Table 5. Awareness and usage of tools

Some of the common issues identified through the interviews include a shortage of experienced advisors, low level of trust in advice given, overly complex tools, low trust in available tools, and a need for a better understanding of nutrient management by farmers, foresters and growers.

Preferred delivery mechanisms for nutrient management science

When delivery mechanisms were discussed respondents predominantly talked about human based interactions, and translation of complex information into clear

[3] FAR benchmarking study showed for example AMaizN being used for more than individual paddock analysis

and simple messages. Tools were discussed but were not the preferred delivery mechanism per se, rather something that is used by predominantly advisors to support decision making.

Sector	Preferred delivery mechanisms	Comments
Arable	One on one discussions Group options: commitment groups, discussion groups, focus farms, demonstration farms, field days	Individual delivery constrained by shortage of advisors. 'Demonstration' critically important, 'long powerpoints' do not work well
Dairy	Agricultural consultants and fertiliser representatives One page/short planning tools Websites Live demonstrations and small group discussions Multi layered approaches – written, spoken, demonstration Solution focussed rather than information focussed Linking information directly to needs such as council regulations	Consultants and reps can translate science and use science based tools on behalf of farmers[4] Websites popular with councils to disseminate information widely
Forestry	Clear concise reports that combine lab results with on ground recommendations – preferably on one page Fertiliser representatives to give detail on fertiliser options Involvement with research experiments	Simple and clear information that can be easily passed to forest owners for information/decision making On-going communication on the results and implications from nutrient experiments is appreciated for its capacity development benefits but little direct involvement in experimentation itself possible.
Horticulture	As for arable	Balancing complexity and simplicity is critical
Sheep and beef	As for arable	

Table 6. Preferred knowledge delivery mechanisms

Where tools were discussed, issues of complexity arose regularly and the need for simple and clear outputs and recommendations was often stressed. The need for good advisors with a long term understand of the property was also identified. Another issue identified was the 'time poor' nature of farming, forestry and horticultural practitioners and the time required to access some information or use some tools.

B. DISCUSSION

Effectiveness of the implementation of NM Science

As reported in the National review section there has been a significant amount of NMS research undertaken in New Zealand between 1998 and 2013 and this has

[4] Botha, N., Parminter, T, and Bewsell, D. 2008. Learning from success: Adoption of Nutrient Budgeting at Rerewhakaaitu and Toenepi. June 2008

been translated widely for use by the primary sectors. The effectiveness of the implementation of the new knowledge varies across the sectors and this section of the review has identified a number of reasons for this.

Tools and codes of practice are available, however tool use is limited by the complexity of many of the tools and mismatch with what users need. Additionally, there are limited opportunities for up skilling of farmers, foresters and horticulturalists and a reliance on a limited pool of advisers and technical experts who are not necessarily trusted to give independent advice. There are some who consider the technology transfer or implementation process to be broken. . Greater engagement with the targeted users from a very early stage of tool development could potentially enhance use and uptake.

If we consider knowledge translation and transfer; farmer, forester and grower training; and tool development and use as the three key threads that contribute to overall effectiveness of implementation then there are a few areas on the attached diagram (Figure 10) where there are weaknesses. Addressing these will lead to increased effectiveness of implementation and an overall improvement in Nutrient Management practice.

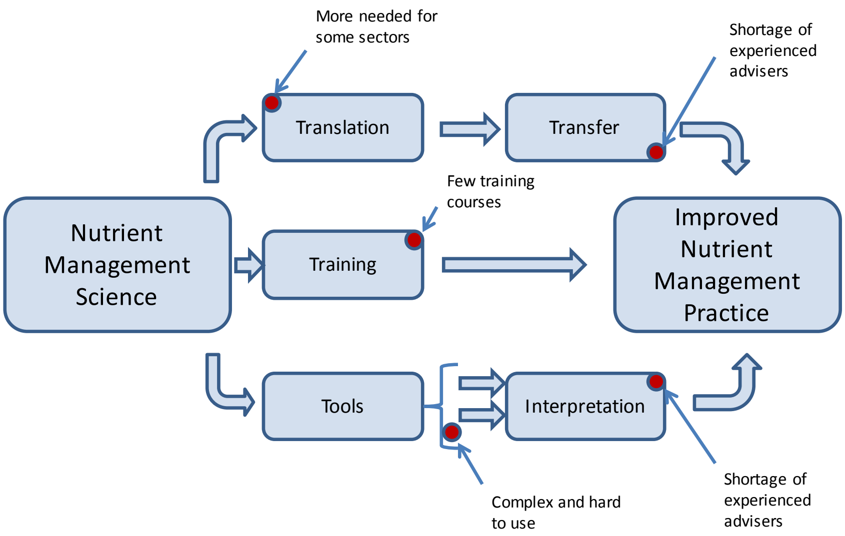


Figure 10. NMS implementation pathways

Of the range of tools available, there was much comment on OVERSEER® which is seen as the benchmark and accepted way of doing things for all sectors except for forestry. There is an increasing requirement for use of OVERSEER® in support of new regulation. A recent FAR review[5] noted that the use of OVERSEER® in a broader policy and regulatory space is new and that the owners have to ensure that it remains fit for purpose in these new uses

Given this new important role of OVERSEER®, there will be a need for further research. For example the OVERSEER® Pastoral model has been field validated on a number of well defined, but narrow range of sites/soils, and it is accepted that further validation is required in other situations (e.g. on stony soils as in Canterbury and Otago). There is also an urgent need for a comprehensive

[5] FAR (2013: 15). A peer review of OVERSEER® in relation to modelling nutrient flows in arable crops. A report commissioned by The Foundation for Arable Research, January 2013.

'sensitivity analysis' of OVERSEER® to be undertaken, so that users can understand and appreciate the likely errors which arise from getting the input data wrong, or at least direct users to those input parameters which have large effects on the predicted N and P losses if they are wrong.

Other comments made in the review concerned application to cropping systems: *"This new (cropping) capability has been developed using a number of simplifications. These are consistent with the approach taken in modelling pastoral systems within OVERSEER® but contrast with approaches taken in other crop-soil interaction models. Although the OVERSEER® crop model has already been tested to a limited extent, more comprehensive testing is needed to determine whether these simplifications impair the model's capability for predicting long-term average nitrate leaching in arable systems. Further testing would also help to build confidence amongst users. The OVERSEER® user interface for crops is also relatively under-developed compared to the pastoral model and is in need of further attention before it will be able to deal effectively with complex crop rotations."*

Past studies [6,7] show the adoption and use of tools seems to follow a pattern where models tend to get used for a while and then use decreases. In the case of farmers the reason is that they learn from using these tools and develop rules of thumb which they then use in place the tools. This reinforces the need for both training in nutrient management amongst farmers, forester and horticulturalists and for the development of clear and concise rules that can be used in place of complex models under common conditions. Forestry uses this approach by doing many model runs and developing simple 'look up tables' for managers

Building trust in the models and tools is important. There need to be a wider range of people using models, support for the users to help them and training and competency in using models. There is a need to build trust in the tools and resources that are available to engage next- and end users. Respondents noted: *"There are examples where tools have been produced and then funding has dried up before an extension stage has been engaged in. This resulted in low tool or resource uptake".* and *"There is a need to have early engagement with intended NM science tool users".*

Gaps in NMS knowledge

Scientists are in general promoting the four R's as a good strategy to follow[8]:
Right fertiliser; **R**ight amount; **R**ight timing and **R**ight place and this message appears to be getting through to users, but they still need additional information to implement these four R's correctly.

[6] N Botha and K Atkins 2004. .Learning preferences of New Zealand farmers. Paper to the Conference on Learning and Human Capability in Agriculture, Hamilton, New Zealand. 23-24 November.

[7] Neels Botha, Bruce Small and Kris Atkins. 2004. Wired" for learning: computers and the Internet in rural New Zealand. Paper to the Conference on Learning and Human Capability in Agriculture, Hamilton, New Zealand. 23-24 November 2004

[8] The four R concept has recently been promoted in an international manual for plant nutrition: http://www.ipni.net/ipniweb/portal.nsf/0/231EA9CAE05F5D24852579B200725EA2

There were specific knowledge gaps identified through the interviews that need to be filled and these vary by sector. Overall there is a need to focus on solutions rather than just information provision. Expansion and refinement of tools is a common theme. Improvement to OVERSEER® for pastoral livestock production, more precision in forestry nutrient recommendations and new knowledge related to other tree species, a better understanding of and capability within OVERSEER® for arable and horticultural crops ahead of expected increased regulation and improved prediction of potential N mineralisation rate for horticultural soils.

DISCUSSION AND RECOMMENDATIONS

It is clear that there has been a very significant and effective investment in NMS in NZ in the last 15 years, and drawing out some key points from the previous sections allows us to see if we are well aligned with international trends in NMS and also whether there are any significant gaps or conversely over investments.

KEY FINDINGS FROM INTERNATIONAL REVIEW

Globally, demand for food will increase and this will ensure continued markets and opportunities for New Zealand Agriculture. Risks to food and fibre production will increase as a result of climate change, and it is likely that fertiliser costs will continue to rise. Concerns about the sustainability of agriculture and forestry systems will lead to more demand for green certification of products, and reduction or mitigation of environmental impacts. International research focus is on increased nutrient use efficiency, enhanced production and lower environmental footprints. These global trends are all directly relevant to NZ and will require a response.

NZ agriculture is different in many respects because of its heavy dependence on pastoral, and consequently the animal is the source of much of the nutrient leakage (nutrient inefficiency) in the NZ system. Furthermore, the dairy production system is quite different to systems in, e.g., N. Europe because it has evolved to operate in an unsubsidized environment. The response in Europe has been to limit inputs and stocking rates and to house animals through the winter months requiring expensive infrastructure and manure handling facilities, and more imported feed. The challenge for New Zealand is operating profitable production within the constraints of world market prices. The challenge for nutrient management science is therefore to assist in the design of nutrient efficient production systems that are economically, as well as environmentally, sustainable. Our assessment of research to date is that the focus has been on this; the continuing challenge is being able to achieve this under increasingly tight environmental demands.

KEY FINDINGS FROM NATIONAL REVIEW

Money well spent? The scope of the research carried out in last 15 years has reflected the needs of the sectors as they emerged and topics have been quite varied and broad. This has provided effective coverage of topics within both the N and P cycles as outlined in the diagrams presented earlier. It has also built on the considerable amount of research done prior to the 15 year period covered in this study. Whether the research has been driven by a long term strategy or has been evolutionary and responsive to trends is open for debate, but overall the knowledge base available to farmers, foresters and horticulturalists (FFH) today is very sound. We are well placed to meet future challenges. Research has been undertaken by CRIs (predominantly AgResearch, Plant and Food Research, Landcare Research, and Scion), Universities (predominantly Lincoln, Massey and

Waikato), and fertiliser and technology companies and associations. In our opinion no areas appear to have had too much emphasis, conversely no areas have reached a final point where all is known and further work will not be needed.

There are numerous examples of where Nutrient Management Science has had a significant impact on practice such as:

- Development and adoption of Best Management Practices – for example, farm dairy effluent application and management
- Forestry fertiliser management systems have been adopted across at least 80% of the national planted forest estate and enable managers to routinely test for nutrient status and develop economically based fertilisation programmes which have led to overall increases in productivity in New Zealand.
- Rapid growth in the development of paddock scale and whole farm system models. The OVERSEER® Nutrient Budgets model is probably the best known example here, but there are also other examples too (for example, DairyNZ's Whole Farm model). These have been able to capitalise on the NMS base to model nutrient cycling at the farm scale, thus aiding the development and implementation of strategies to improve nutrient use efficiency and to decrease losses to the wider environment. Such tools (and DSS examples, below) are an effective way of translating research into usable science that can be deployed on farms.
- Development and adoption of a wide range of Decision Support Systems across all sectors based on many field based experimental programmes. This has been aided by advances in computer technologies in recent years. Use is variable within sectors but increasing.
- Process inhibitors – New Zealand is a world leader in the use of process inhibitors to manage N cycling, most notably through the direct application of DCD to soils. We have a good understanding of likely efficacy and the factors that affect it, though this understanding does need to be extended beyond the relatively narrow range of circumstances where it has been trialled . Rate of uptake by the industry is related more to cost and drivers for its use, than lack of science understanding.

Knowledge Frontiers and critical gaps

- ***Crop/pasture nutrient demand***. The basis to effective nutrient management starts with reliable predictions of how much nutrient crops need and when. This can be affected by any number of dynamic and static factors – many of which are not adequately considered in current decision making processes. Many recommendations are based on productivity targets that are not realistic.
- ***Spatial and temporal variation in urine patch N load***. There has been significant research on understanding the soil N cycling processes that occur under a urine patch. However, there is still not a good understanding of the variation in urine patch N load, the key factors affecting it, ability to model/ predict it, and implications for estimating losses from the urine patch to the environment. This is critical information, requiring data on N concentration, urine volume and area of the patch.
- ***Econometric modelling***. In the context of NUE and nutrient runoff, optimal nutrient levels need to be managed at the economic optimum. An economic nutrient model, owned by the fertilizer industry, calculates the

economic optimal nutrient levels for any given pastoral farm (not N). There is scope for updating this model with more recent research (and FANZ are planning upgrade their proprietary software).

- Research to underpin the development of sustainable farming encompasses ***economic assessment or cost-benefit analysis***. Many projects at the farm systems level include an assessment of cost and cost-effectiveness of management strategies. Technologies to decrease nutrient losses have also been assessed for their cost-effectiveness in a range of situations. There is a good appreciation that nutrient management science must address all three pillars of sustainability.
- ***Increasing complexity of farm systems***. Demands on farmers, foresters and horticulturalists are increasing. Emphasis is on far more than productivity alone with market requests for demonstration of green credentials, local government needs for enhanced environmental management, and continued economic challenges such as fertiliser and shipping costs or exchange rates fluctuations. Managing for these varied outcomes is difficult and some FFH's are struggling.
- ***Improving P use efficiency.*** Inputs of P to NZ pastoral farming systems are, on average, about 5 times that removed in produce. Can we improve the management of existing P reserves to sustain high levels of production while reducing the need for P fertiliser inputs? Is it possible to the mine the substantial reserves of P that have accumulated in many NZ soils? Given growing concerns regarding future P security/scarcity, reducing New Zealand's high reliance on imported P by improving agricultural use efficiency should be given some priority. Most of the fertiliser P used in NZ is applied to pastures and pastoral land uses can have large P surpluses (inputs >> outputs) compared to arable cropping. In sheep production, for example, P off-take in animal products may only be 1-4 kg/ha whereas the recommended P maintenance requirement can be~ 20 kg/ha. Substantial reserves of P have accumulated in many NZ pastoral soils as a result of historic applications. The nature and plant-availability of these reserves needs to be understood so that they can be managed to sustain high levels of production while minimising the need for fresh P fertiliser inputs.
- ***Legumes as a source of N input.*** Legumes are an important source of BFN and the major N source in some pasture production systems, notably hill country pastoral systems. However, there is little current research on legume agronomy and improving survival and function of legumes in pastoral systems (again, most notably but not exclusively, upland systems).
- ***Mitigating losses from grazed forage crop systems***. Grazed forage crop systems typically have very high and concentrated returns of N, P and K in animal excreta. With the rapid expansion of these supplementary feed systems there is need to identify management practices that mitigate the losses of nutrients, including the gaseous and leaching losses of N and runoff of P into waterways. These are nutrient intensive hot spots in the NZ agricultural landscape.
- ***Animal management*** was considered out of scope for this review, but it is clear that this component of the production system is also being targeted as a way to improve nutrient use efficiency (and may warrant a separate review).
- ***Nitrogen mineralisation***. Predicting the real time supply of plant available mineral N from soil organic matter turnover remains a very high priority for nutrient management science in New Zealand. This appears to be particularly important in NZ where many of our soils tend to have relatively

high organic matter levels and capacity to mineralise substantial levels of mineral N. To achieve this goal we need to define the size of the potentially mineralisable N pool and understand the factors that regulate its release over a growing season or seasons. With increased need for precision in nutrient management across all sectors, both spatially and temporally within the crop cycle, this process is integral to any advances in nutrient management. Mechanisms to switch on or accelerate mineralisation for example will allow forestry to increase its productivity levels within the 30 year crop cycle without application of fertilisers. Nitrogen capital is often adequate in forest soils, but availability is not. Precision agriculture techniques in annual crops will also benefit significantly from better ability to manage N mineralisation.

- ***Nutrient Use Efficiency*** is a key integrative indicator of NMS success but NZ currently does not pay enough attention to this indicator which is widely used globally. Increased NUE can have multiple benefits – increased productivity, lower fertiliser costs, better economic returns, lower environmental impacts. Development of statistics and targets for NZ FFH would be very helpful in a range of forums, for example green market credentials. The indicator itself would require careful development and interpretation due to its multivariate nature but would be a very powerful tool for use both at the property, land use, catchment and national scales.

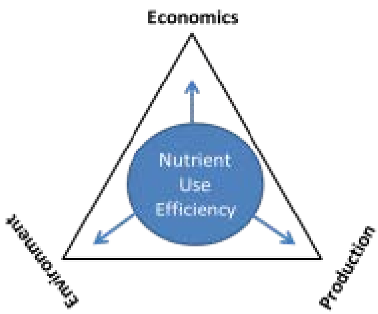


Figure 11: Nutrient Use Efficiency

It could be argued that NZ, through its farm modelling tools, is considering NUE but not overtly. The drive for increased profitability through efficiency gains will also benefit improved nutrient use efficiency.

- ***Trust and use of NMS knowledge and tools***. The body of knowledge and tools available to FFH and their advisors is large. However, tools appear to be variably used, use is potentially inappropriate, and the tools are often seen as too complex. So there is an issue of design and implementation of tools to make the best use of NMS – simple planning tools are preferred, but this has to be balanced against the fact that we are dealing with complex systems. Trust in the knowledge and tools is an issue also. It is apparent that there are occasions of misuse of fertilisers for example due to farmers unwilling to agree with the reasoning behind reducing P application rates on soils which are becoming 'overcapitalised' for this nutrient.
- ***Nutrient interactions:*** While this review has focussed on N and P, it is apparent that other elements especially minor nutrients are gaining increasing attention and that the interactions of these elements with N and P should not be overlooked.

- ***The science, technology and research uptake model:*** One of the strengths of NMS research done to date has been the link between fundamental research into soil and crop processes, the application of those findings into applied research, the development of models and tools, and their subsequent use by stakeholders. It is crucial that the cycle as outlined below (Figure 12) is maintained in any future research. Management based on shaky science or a poor understanding of the underlying processes will be high risk.

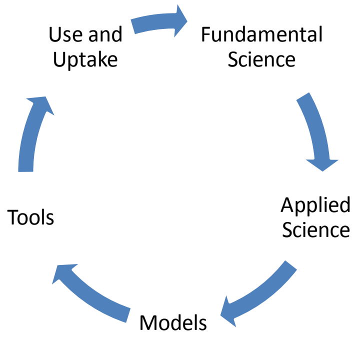


Figure 12: Science, Technology and Uptake Cycle

National science capability and capacity and associated infrastructure are also very important to maintain momentum in the NMS area. Good interaction within the science community, multidisciplinary approaches and maintenance of a balanced science demographic is crucial (currently the latter is skewed towards an older age cohort of scientists). Maintenance of long term science infrastructure such as long term experiments (e.g. Winchmore - pastoral, Puruki - forestry) has been shown to be invaluable.

- ***Maintenance of long term science infrastructure*** such as long term experiments (e.g. Winchmore - pastoral, Puruki - forestry) has been shown to be invaluable. As stated by McDowell & Smith (2012): the Winchmore field trials represent some of New Zealand's longest running scientific experiments and, globally, the longest running trials of grazed and irrigated pasture. Since their establishment over 60 years ago, data from the trials have been used in nearly 500 publications. However, this is only a partial measure of the trials' value. More poignant measures include recognition of the role Winchmore played in establishing dairying in Canterbury, the importance of phosphorus (P) and sulphur (S) to soil fertility, and the establishment and management of irrigation systems that underpin much of the rural economy in Canterbury. Similarly, according to Mackay & Lambert (2011): the ability of scientists to report on the long-term consequence of a change in the fertiliser use on pasture and animal production was based on access to the findings from a series of long-term fertiliser and grazing studies. In that regards, for example, the long-term fertiliser and sheep grazing farmlet study at Ballantrae provides invaluable data sets on the long-term influence of P fertiliser on soil fertility and biology, pasture ecology and animal production that is of interest to both science and producers. It also provides an invaluable field laboratory for extension.
- ***Other nutrients:*** The report focuses on N and P, with some mention of other nutrients. This is understandable because they are the two nutrients of concern from an environmental perspective. However, other nutrients are

important for sustainable agriculture. These nutrients are essential for growing good crops (and for animal health) which, in turn, make efficient use of N and P. This is partly a technology transfer issue (i.e. continue to promote the good science that has been done historically on these topics, to ensure that it is taken up by sectors). However, it is also important to ensure that the research portfolio does not omit these subject areas. Furthermore, there is potential for a decline in the national capability in the science of these other nutrients if there is no investment in these areas.

KEY FINDINGS FROM USE AND UPTAKE

While there is considerable awareness of key tools available—particularly models, trusted advisors and experts and core documents— there is limited uptake of the direct science knowledge and tools at a practitioner level. Where farmers and foresters seek knowledge, they generally know where to go to get it, and therefore can obtain the information they seek readily. However, this tends to be a 'fire-fighting' approach to fixing immediate issues rather than leading to up-skilling in best management practices or latest techniques.
Farmers, growers and foresters are all constrained by both time and money from the application of up-to date information and up-skilling in nutrient management science. They therefore rely on trusted advisors (farm reps, consultants and science advisors) to provide assistance or provide laboratory recommendations for nutrient application, based on foliar and soil analysis. There needs to be an appreciation that the tools and models developed by CRIs (OVERSEER, Forecaster, AmaizeN etc.) are not user intuitive nor designed at farm-level or site specific analysis. Most tools and models still require a degree of expert analysis to interpret best management practice at the farm level. One-one sessions via on-farm demonstrations, regular science-advisory from extension officers, or developing rapport between nutrient management scientists and the end user groups should be encouraged to enhance the technology transfer system in primary industry. One of the key issues is to address the lack of independent advice, and to develop trust with the sectors. The high turnover in fertiliser reps, combined with the tendency of fertiliser companies to change brand allegiance for core product ranges erodes the ability to develop long-term rapport with users.

Farmers, growers and foresters all rely on practical experience and past results to make nutrient management decisions, which are overlaid with a cost benefit analysis. The cost of fertilisers, and the need to farm sustainably is driving a reduction in the blanket application of fertiliser towards more targeted application. Particularly, users desire to a) see a return on the nutrient investment, in terms of improved yields or health of the crops, and b) are increasingly aware of environmental and regulatory pressures to keep applications to a minimum. Efficient application of nutrients through applying the right amount of the right nutrient, at the right time, to the right site is critical to farming success. Knowledge that can aid this practice is highly sought.

NEXT STEPS AND CHALLENGES FOR NUTRIENT MANAGEMENT SCIENCE

CONTEXT AND FRAMEWORK

International demand for New Zealand's Agricultural, Forestry and Horticultural products is likely to continue to grow given population trends, and this is a great opportunity for the country. Growth in production has its challenges, and New Zealand's response to these challenges will determine how rapidly we can realise the opportunities for growth. We will need to grow production and exports but not at the expense of our natural resources – markets are increasing demanding 'green products'. In 2009 New Zealand was one of 34 countries that signed an OECD Declaration on Green Growth. This has subsequently led to the recognition in New Zealand of Green Growth as an enabler of growth and development and the Government's Business Growth Agenda incorporates these concepts.

The outcomes from this review can be put in context of Green Growth and the Business Growth Agenda. Two goals are of the most relevance to the Nutrient Management Science topic:

1. Increase the ratio of exports to GDP to 40% by 2025 (Building Export Markets)
2. The quality of our natural resource base improves over time while sustaining growth needed from key sectors to meet our 40% exports to GDP target (Building Natural Resources)

Within New Zealand there are a number of national initiatives related to these overall goals where nutrient management science can contribute significantly especially within the water sphere where land management will have to work within new water quality and quantity limits and meet national minimum environmental states (MfE 2013).

We have captured these concepts within three outcomes: increased production/exports; green market credentials/market access; and maintaining and enhancing environmental quality. We then outline where we consider NMS research could make the most impact in the future.

The environment in New Zealand is changing in a number of ways. The climate is expected to change in the future, to be warmer and drier in the east and north, and warmer and wetter in the west. Increasing frequency and intensity of rainfall is also expected generally. Atmospheric CO_2 levels are projected to continue to rise. Environmental quality of water bodies is poor generally, often as a result of past agricultural activities and numerous activities are underway to halt and reverse this decline. These projected changes to the environment must also be factored in to any future nutrient management science priorities.

Emerging areas: Advances in soil and plant biotechnology methods make this the most rapidly emerging area of NMS research. Shift of emphasis from chemical to biological could have far reaching implications for both sustainable management and soil health. Precision agriculture, forestry and horticulture technologies are also very significant opportunities – marrying silicon based and biological systems.

Integration - joining the dots to support decision making. The body of knowledge is now such that there are opportunities to make significant advances through integration of knowledge and tools into systems that can improve decision making at the whole farm scale. We are working with increasingly complex systems and we will need systems models to allow us to best manage or optimise these systems for the multiple outcomes (economic, environmental and social) that are becoming very important for the primary sector. More than ever production is being driven by markets and market perceptions of agricultural, forestry, and horticultural practices. Additional to management at the whole farm scale will be the need to manage at the catchment scale with multiple enterprises within a catchment.

Uptake and continued development of technologies. Improvements in nutrient management need to continue, as new challenges occur. For example, uptake and continued development of technologies such as precision farming, improved irrigation need to continue. The development of new mitigations needs to continue, so as to decrease nutrient losses and increase NUE. Underpinning basic research is required to support this development of applied tools/technologies.

RECOMMENDED PRIORITY RESEARCH AREAS

Future research activity must cover the cycle of research, technology, and use as presented in Figure 12. So a balanced approach is recommended.
A summary of areas for future research building on existing knowledge bases and expected needs for New Zealand is outlined in Figure 13 with more detail on these research needs following.

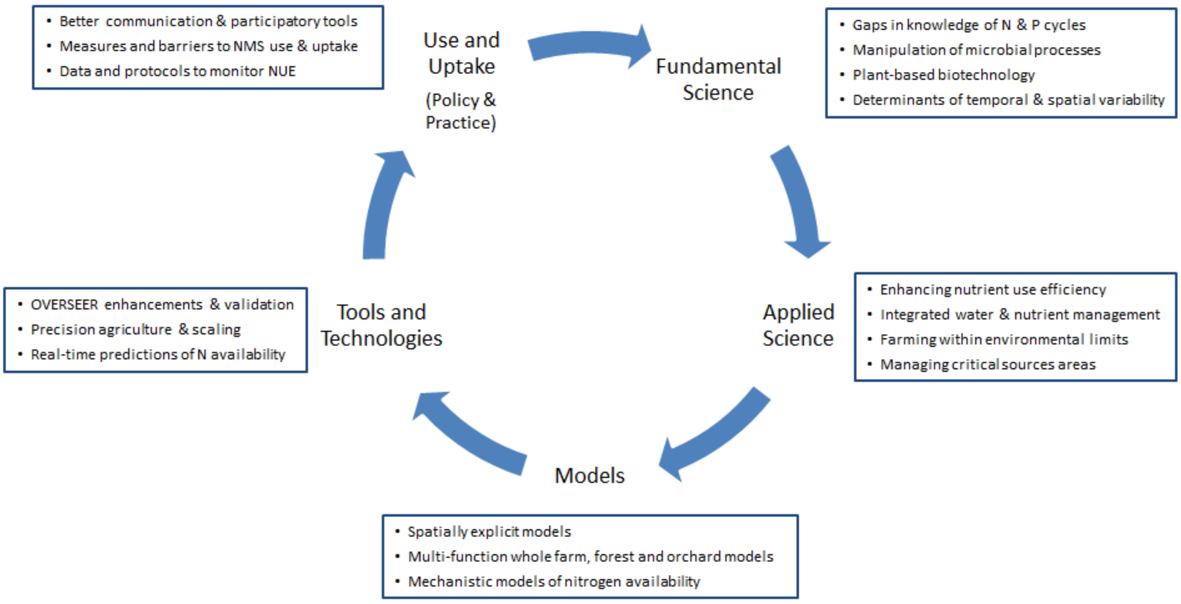


Figure 13: Recommended Priority Research Areas

Areas identified are broad and almost all areas researched in past years could benefit from continuing research and development to make the most of new technology developments and increased systems understanding. The bullets in the cycle above are an effort to encapsulate the most important topics in one diagram. It can also be seen that some topics in their own right are very large – precision agriculture for example could focus on many things from fertiliser granulation technologies to space based remote sensing tools. Likewise sustainable intensification covers a wider spectrum of topics. The outcome from investing in the spectrum of research will be a far more integrated and holistic ability to manage nutrients within agriculture, horticulture and forestry at a range of scales from farm through catchment to national. Within these broad areas however we have identified high priority topics in some more detail and these are outlined in the next section.

The priorities for research within in the cycle of science, technology development, and use are described in more detail as follows:

Fundamental Science

Gaps in knowledge of N & P cycles: Although the primary components and key processes drive N and P cycles are well known, our understanding of the biogeochemical factors that regulate some of the important transformation and transport processes and the size of some key pools and fluxes is poorly known. These knowledge gaps are important constraints to our ability to accurately predict (model) these processes and develop management practices that increase nutrient use efficiency and mitigate losses.

Predicting the soils capacity to supply plant available nutrients is important to forecasting the fertiliser requirements of plants and identifying the risk of nutrient losses to the environment. Some of the critical gaps in our knowledge include:

***Nitrogen mineralisation*.** Improving predictions of N availability during the growing season depend on defining the size of the mineralisable N pool in soils and predicting how much of that N is mineralised over a growing season (or part of a growing season) as a product of changes in the temperature, moisture and other key environmental factors. Developing the knowledge and tools required to accurately predict supply of plant available N from the mineralisation of soil organic matter remains a very high priority for nutrient management science in New Zealand. Understanding the complex interactions between soil organic matter (quantity and quality) and the physical and chemical properties of soils that affect the mineralisation of N over a growing season is critical to achieving this goal and a priority for future research.

Manipulating microbial processes: Microorganisms are responsible for many of processes that directly affect the supply and losses of nutrients from soils. Physical and chemical factors in the environment interact to affect the rate and extent of these microbial processes. Developing a quantitative understanding of how these factors interact to affect key nutrient transformation processes and their biological optima are important to developing management strategies that better match nutrient supply and availability with plant demand during the growing season.

Plant-based biotechnology: With climate change, demands for more food and fibre, and environmental issues on the horizon plant breeding and other plant biotechnologies will increasingly be used to develop crops with new characteristics. Understanding the fundamental physiological processes and their genetic and environmental controls will be necessary to better match crop with site for any given product or outcome. Nutrient and water use efficiency of tree crops is an area of increasing interest for example where forestry is looking to make the most of increasing atmospheric CO_2 levels, in an environment that may be significantly warmer and drier within the 30 year lifetime of the crop, and where higher yields are also sought.

Determinants of temporal and spatial variability: Understanding the primary determinants of temporal and spatial variability in soil/plant systems is important to developing practical management solutions to improve nutrient use efficiency and mitigate losses.

> *Spatial and temporal variation in urine patch N load*. Much recent research has focussed on understanding the soil N cycling processes under a urine patch. However, there is still not a good understanding of the variation in urine patch N load, the key factors affecting it, ability to model/ predict it, and implications for estimating losses from the urine patch to the environment. This is critical information, requiring data on N concentration, urine volume and the area impacted by the patch.

Applied Science

Enhancing Nutrient Use Efficiency: There is a growing emphasis in nutrient management science world-wide on increasing nutrient use efficiency. Two key areas have been identified as priorities in New Zealand.

> *Management to improve P use efficiency on pastoral farms.* New research should focus on developing fertiliser technologies and/or agronomic practices that ensure more efficient use of the P that is applied to pastoral systems. Where soils are known to have a high capacity to fix P, fertiliser technologies could be developed that modify the soil chemistry around the fertiliser granule and slow the reactions that make P increasingly unavailable with time. Where concentrations of fixed P are high, technology that would permit the mining of those P reserves could help to reduce the reliance on P fertiliser inputs to sustain high levels of production. It could also help to future proof the fertility of pastoral farming systems in the event of limitations to supply or increased costs.

> *Legumes as a source of N input.* Legumes are an important source of biologically fixed N and a major N source in some pasture production systems, notably hill country pastoral systems. However, there is still a need to improve the agronomic management of legumes, particularly the survival and function of legumes in pastoral systems (again, most notably but not exclusively, upland systems).

Integrated water and nutrient management: Water is a key factor affecting the transformations, transport and uptake of nutrients in soil/plant systems. Understanding the interactions between soil organic matter and soil physical properties as they affect the transformations, transport and uptake of nutrients in and on soils is important to optimising the management of water and fertiliser inputs to ensure the most efficient use of these resources.

Farming within environmental limits: Research is needed to better define the range of management practices used by the agricultural, horticultural and forestry sectors on different soils and to use models to predict the impacts of the these practices on nutrient uptake and losses under different climatic conditions. Quantifying the environmental and productivity gains that can be made from applying realistic and achievable good management practices to different soils and climatic zones will be important to informing regional land and water management policy development and targeting the establishment of alternative practice to high risk zones.

Managing critical source areas: Identifying the critical source areas for nutrient losses to the wider environment is important to developing policies and practices that achieve the greatest environmental gains.

Management to mitigate losses from grazed forage crop systems. Grazed forage crop systems typically have very high and concentrated returns of N, P and K in animal excreta. With the rapid expansion of these supplementary feed systems there is need to identify management practices that mitigate the losses of nutrients, including the gaseous and leaching losses of N and runoff of P into waterways. These are nutrient intensive hot spots in the NZ agricultural landscape where a reduction in nutrient losses could have greater benefits for reducing the environmental footprint of the entire pastoral sector.

Models

Spatially explicit models: Models that account for spatial variability in soil/plant systems are needed to evaluate the consequences and benefits of spatially explicit management practices at the paddock and whole farm scale.

Crop/pasture nutrient demand. The basis to effective nutrient management starts with reliable predictions of how much nutrient crops need, when they need it and where. This can be affected by any number of dynamic (e.g. physiological responses to climate factors) and static (e.g. soil physical constraints) factors – many of which are not adequately considered in current decision making processes and can lead to recommendations that are based on unrealistic productivity targets. These gaps need to be filled in order to ensure proper estimates of nutrient demand are applied in forecasting fertiliser requirements of crops/pastures and predicting nutrient residuals and losses.

Multi-functional whole farm models**:** The development of fully integrated econometric, environmental and social response models of whole farm systems are need to identify the full spectrum of outcomes and unforeseen consequences associated with applying specific nutrient management practices aimed at producing more sustainable farming systems.

Mechanistic models of nitrogen availability*:* The use of models to accurately forecast the fertiliser requirements of crops, pastures and forests depend on being able to predict the availability of N for plant uptake during different stages of plant development. Nitrogen availability is a product of the starting mineral N concentrations in the soil profile, and the N mineralised, the N taken up by the plant and the N lost from the root zone (either by leaching or gaseous emissions) over a fixed time interval. Improved knowledge of the factors that regulate N mineralisation and transport processes is critical to the development of models that predict N availability from the integration of these processes.

Tools and Technologies

OVERSEER® enhancements & validation: The nutrient management tool OVERSEER® is an important tool for the pastoral sector. It is an effective route to move science into the farm. However, it needs further validation and testing. Further validation of the pastoral component is required to cover situations outside of the currently available data (e.g. on stony soils as in Canterbury and Otago). A more comprehensive validation assessment is also required for the cropping model.

Precision agriculture & scaling: Precision farming research advances in New Zealand over the last fifteen years have identified a number of methods and applications which can provide significant benefit to assist on-farm nutrient management. The challenge is not only to continue these technical developments but also to drive on-farm adoption and integration into farming systems so that these benefits are realised.

Real-time predictions of N availability: Improving predictions of N availability during the growing season are important to forecasting the fertiliser N requirements of plants (crops, pastures, trees) and mitigating the risk of N losses to the environment. Real-time estimates of N availability depend on being able to accurately predict the mineralisation of N from soil organic matter, the vertical stratification and losses of mineral N due to leaching and gaseous emissions and amount of mineral removed by plant uptake. The development of advanced soil-plant-environment models that accurately predict these processes and the impacts on soil N availability are need to apply the fundamental knowledge gained above and improve N use efficiency on the farm.

Use & Uptake (Policy & Practice)

Better communication and participatory tools: The body of knowledge and tools available to farmers, foresters and horticulturalists and their advisors is large. However, tools appear to be variably used, use is potentially inappropriate, and the tools are often seen as too complex. So there is an issue of design and implementation of tools to make the best use of NMS – simple planning tools are preferred, but this has to be balanced against the fact that we are dealing with complex systems. Trust in the available knowledge and tools is also an issue. Encouragement for longer-term relationship building between the science advisor and farm system could be assisted through policy instruments

Measures and barriers to NMS use & uptake: The effectiveness of NMS in New Zealand hinges on our ability to measure its use and uptake by targeted end user groups. The development of robust tools to measure use and uptake is critical to identifying the most effective tools and communication pathways for delivering the practical applications of NMS, but also to identifying any barriers to their uptake. Understanding what constitutes effective uptake of the science is central to developing robust measures of use and uptake.

Protocols & data to monitor NUE: Monitoring the performance of New Zealand's nutrient management policies and practices depends on deploying robust protocols for reporting on the productivity and environmental impacts that follow from the use of nutrients within agricultural systems. The ability to more effectively monitor NUE at a farm level would assist in developing practices that increase productivity, lower fertiliser costs, improve economic returns, and lower environmental impacts. The use of agreed metrics and targets across our agriculture, horticulture and forestry sectors would also be useful for international reporting and promoting New Zealand's green market credentials. The indicator(s) would require careful development and interpretation due to its multivariate nature but would be a very powerful tool for use both at the property, land use, catchment and national scales.

ACHIEVING THE REQUIRED OUTCOMES

We identified three key outcome areas: increased production/exports; green market credentials/market access; and maintaining and enhancing environmental quality. The priority areas are mapped to these outcomes in Figure 14. There is a fairly even balance between priorities focused on production (business growth agenda – exports) and environmental quality (business growth agenda – natural resources), and fewer on market access. A number of priorities contribute to two outcomes – mainly at the production and environmental interface and two contribute to all three outcomes.

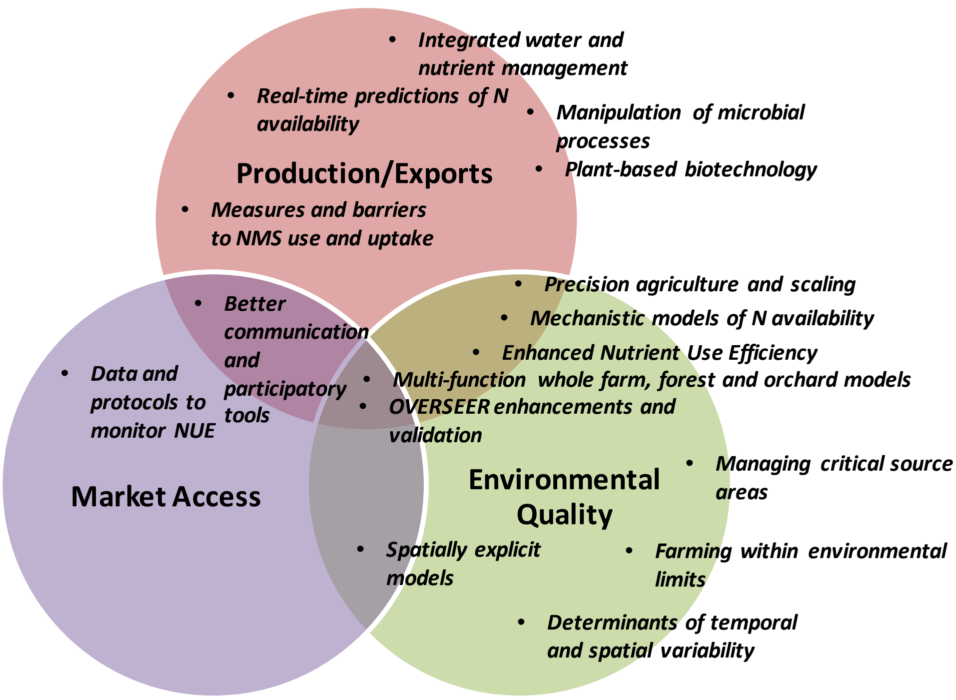


Figure 14 Mapping priority research areas to key outcomes

Increased production/exports: Better matching nutrient supply to crop demand within the crop/rotation cycle and exploring the upper limits of crop physiology for dry matter production should be a focus for this outcome.

Maintaining and enhancing environmental quality: Water quality in New Zealand is declining as a result of past land use practices. Intensification of production will put increased pressure on the systems making this an area of very high importance. Reducing nutrient emissions – both from leaching and volatiles has a twofold benefit: economic - from the more effective use of costly fertilisers, and environmental - in terms of improved water quality.

Green market credentials/market access: If forestry is an example of future pressures on agriculture as a whole, certification systems and green markets will pressure producers to minimise chemical usage in their systems. This is a major driver under the international Forest Stewardship Council and is having significant impact on the way New Zealand companies manage their forests. So with this in mind for the New Zealand primary sector there are a number of research areas to be explored: Benchmarking nutrient inputs and measures of the nutrient footprint or nutrient use efficiency (now a major global agriculture indicator). There are currently no readily available data on this across the primary sector to support assertions of environmental credentials.

To support these priorities national science and technology capability will need to be maintained and further developed into new areas. As noted previously there is an aging science demographic in New Zealand and some large gaps in national capability in the extension/technology transfer area.

GLOSSARY

APSIM - Agricultural Production Systems Simulator
ATP – Adenosine Tri-Phosphate
BFN – Biologically Fixed Nitrogen
CC –Climate Change
CLUES - Catchment Land Use for Environmental Sustainability model
CRI –Crown Research Institute
DCD - Dicyandiamide
DM – Dry Matter
DNA – Deoxyribonucleic Acid
DON – Dissolved Organic Nitrogen
EM - Mapping
EU – European Union
FAR – Foundation for Arable Research
FDE - Farm Dairy Effluent
FFH – Farmers, Foresters and Horticulturalists
FFR – Future Forest Research
GIS – Geographic Information System
GM – Genetic Modification
GPS – Geographic Positioning System
GWP – Global Warming Potential
LEP – Land Environmental Planning Toolkit
MBIE- Ministry of Business, Innovation and Employment
MPI- Ministry for Primary Industries
NM – Nutrient Management
NMS – Nutrient Management Science
NUE - Nutrient Use Efficiency
NZ- New Zealand
Olsen P – Soil phosphorus test
PUE – Phosphate Use Efficiency
RM Science
RNA – Ribonucleic Acid
RPM –Rising Plate Meter
RPR – Reactive Phosphate Rock
Superphosphate
SOM – Soil Organic Matter
Sward – noun: the grassy surface of land, an expanse of short grass
VRAT - Variable Rate Application Technology(ies)
UAV –Unmanned Aerial Vehicle

APPENDICES

APPENDIX 1 – SCHEDULE 1: THE SERVICE

SCHEDULE 1

THE SERVICE

16271 – Nutrient Management Review

1. INTRODUCTION

This contract is to conduct a Review of Nutrients and Nutrient Management Science (NMS) and the extent this knowledge has been used by stakeholders in New Zealand over the past 15 years.

2. BACKGROUND AND RATIONALE

Discussions with MPI stakeholders have highlighted the investment spent in this area, by MBIE and MPI with uncertain outcomes from this research. Recent cabinet papers on the water reforms have sought information on research to date as it affects water quality as well. This has raised the question of what has been researched, and how effectively has it been used. As nutrients are the single biggest expenditure item on farms, effective use of research knowledge is important and may save significant expenditure and improve on farm profitability.

The expected benefits and outcomes from this project are that MPI will be in a better position to target advice and policy on nutrients and nutrient management to stakeholders and research funding agencies including MPI. MPI should be able to provide information on knowledge frontiers and identify gaps and areas of acceleration that will be most useful to stakeholders and policy. It will partially contribute to the Water Team needs as well.

3. SERVICE DESCRIPTION

The services will deliver a report synthesising the knowledge of areas of research on nutrients and nutrient management, their priority and impact, research frontiers and gaps and the extent this knowledge has been adopted by policy or farmers

A desktop review of research conducted on nitrogen, phosphorus and comments on other nutrients over the past 15 years, excluding the impacts on water, as well as a survey of the use of this research by stakeholders.

4. SERVICE REQUIREMENTS

The Contractor shall undertake the review in four sections:

1: Survey international trends in NMS

2: Understand the state of NMS knowledge in NZ

3: Review the use and effectiveness of NMS application in NZ

4: Report on the findings

1: International trends in Nutrient Management Science (7.0%)

A brief review of international literature will be undertaken to understand global trends in NMS and associated technologies (e.g. the nutrient management chapter of the Millennium Ecosystem Assessment (MEA) http://www.millenniumassessment.org/document.314.aspx.pdf.theEurpean NitrogenReview.theInternationalFertiliserFederation). Particular focus will be placed on N and P and on NMS for both increasing productivity and minimising environmental impacts. International science networks will be used where appropriate to better understand global issues and trends.

This will enable the contractor to identify the international knowledge frontier and key trends, issues, policy interfaces and key players that NZ will need to be aware of with respect to NMS and aid in the NZ focussed gap analysis

2: State of Nutrient Management Science in New Zealand (50%)

This part of the review will be segmented at a number of levels to cover the primary sector crops and New Zealand's environment:

The hierarchy (matrix) is:

- Nutrients (N, P, other where appropriate)
- Nutrient sources (e.g. fertiliser vs. effluent, RPR vs. superphosphate)
- Processes/Impacts/Interactions, (things that affect ability to give good management advice – e.g. leaching, soil microbial processes)
- Spatial Environmental Framework (soil orders, groups)
- Outcomes
    - Productivity
    - Environmental Impacts
- Sector specific issues (sheep and beef, dairy, horticulture, forestry, arable)

The New Zealand literature will be summarised – both peer reviewed scientific and the grey literature such as technical reports. Brief state of knowledge summaries will be developed for each matrix cell. The review work will be summarised in spreadsheet format and associated key references attached to cells where appropriate.

The gap analysis will be developed by the lead authors, based on the state of knowledge, perceived scale of need by sector and reflecting on international trends. This will then allow the contractor to develop a view of opportunities for improvement to NMS in NZ within the matrix. For example the contractor may identify that for a certain soil type NMS is very under developed for a certain crop, or a need exists to address issues around changing systems e.g. from clover legume based systems to nitrogen fertiliser based systems. The gap analysis will enable comment on future issues or opportunities.

3: Nutrient Management Science Use by policy makers, practitioners (farmers, foresters, horticulturalists) and their advisors/policy makers (28%)

The contract will use a targeted survey and interview approach to determine what of the science knowledge is being used, how it is delivered to stakeholders (e.g. tools, professional advice) and how effective the application of the knowledge is.

A survey will be designed by a small team of social scientists and applied to answer questions on what NMS tools are used, sources of NMS information, current NMS uptake levels and effectiveness of implementation of NMS through for example policy mechanisms

This approach will allow the contractor to then determine where gaps occur and areas to focus on to enhance wider use of the knowledge (‘off the shelf and onto the land’).

Focus on the survey and interviews will be on Industry Associates (e.g. NZFOA, DairyNZ, FertResearch), Fertiliser companies (e.g. Ravensdown, Ballance Agrinutrients), Advisor associations, Regional Council SIG, MPI staff and the project steering group established by MPI. This will enable the contractor to gather a national picture in an efficient way. The synthesis of the results will be carried out by the team responsible for the survey and interviews and passed to lead authors for incorporation into the overall report

4: Delivery of project and transfer of results (15%)

The project will be delivered to MPI as a report structured into the topics as above that identifies the knowledge frontier and gaps and recommendations for improvements, as well as state of knowledge and areas for best practice. The kernel of the report will be the database/spreadsheet which puts the nutrient management science knowledge and practice into an environmental (soils based) framework. This will potentially allow the content of the report to be formatted for web enquiry at a later date. This could be through web portals such as MPI’s, or the National Land Resource Centre.

The project team will follow up the report with an e-seminar to MPI and stakeholders and submit a paper to a suitable international peer reviewed journal.

5: Peer review

The project team will fund external peer review of the report by 2 recognised national experts. Additional peer review is expected from the Oversight Group established for this project to ensure all aspects of the review are covered.

5. MILESTONES

Milestone No	Milestone Title	Description	Delivery Date	$ to be invoiced (excl GST)
1	Review framework established	Oversight group established by MPI (to include MPI representatives, MBIE, sector reps and lead researchers) Draft reporting framework developed – a short document listing the expected report content and sections	30 March 2013	
2	International Review	Key points summarised to feed into NZ phase of review	8 April 2013	
3	NZ Review	Progress report to MPI	14 April 2013	
4	NMS Knowledge Use and Effectiveness Review	An interim document that: Summarises key findings on NMS knowledge usage and effectiveness by landowners, managers and advisors	14 May 2013	
5	Draft Report	Draft report for feedback from MPI and peer review by external experts and oversight group	31 May 2013	
6	Final Report	A final report seminar and draft paper has been provided to MPI prior to submission to suitable journal.	24 June 2013	
	Total			