Soil and nutrient management: the practitioner's perspective

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Abstract
The fundamentals of nutrient cycling over the past three decades are basically the same but the breadth of subject matter and scale of implementation of soil and nutrient management have changed. Soil is considered for its biological and physical attributes in addition to chemical properties. Farms/orchards are managed at significantly finer scales at paddock or sub-paddock level. The resilience of nutrient management now must consider the contexts of climate change influences, social licence, water quality outcomes and those decisions made and implemented by a more highly trained and scarce people resource.

Keywords: advice, environment, fertiliser

Introduction
The purpose of this perspective paper is to briefly discuss how evidence-based soil and nutrient management assists in the resilience of New Zealand grazed pastoral systems. There will be a clear focus on nutrients, fertiliser use and nitrogen (N) loss from grazed pastures. Impacts of environmental regulations targeting water quality and soil condition, and the pitfalls of short-term workarounds to address symptoms, as opposed to finding solutions to the root causes, will also be examined.

Soils – the foundation in which resilient pastures grow
The essence of pastoral farming is to turn the energy of the sun into food energy and fibre. Soils are central to pastoral agriculture and in New Zealand we are arguably blessed with many great soils and for the most part an equitable climate. Pastoral soils function as complex ecosystems and are hugely interdependent mixtures of chemical, biological and physical processes. Agriculturally productive soils are a combination of clay, silt, sand, organic matter (OM), air, water, macro- and micro-organisms and nutrients.

Soil physical condition (contains excerpts from Roberts 2017)
The physical nature of soils is influenced by the different amounts of clay, silt and sand in them. 'Heavy' soils have a high amount of clay relative to the others, while sandy soils have - well - more sand than silt and clay! Approximately equal mixtures of clay, sand and silt usually result in very physically robust loam soils. However, there are an endless number of combinations of the three inorganic constituents of soil which creates a large range of soils with varying textures. Soil OM, largely comprised of dead, decaying or decayed plant and animal matter, is also hugely influential in the structural integrity of the soil. Generally, the more soil OM the better and in New Zealand pastoral agricultural conditions our soils are well endowed with OM, returned from dung, uneaten herbage and root death and decay.

Soil OM interacts with clay and, to a lesser extent, silt and sand to form structural soil particles (colloids) which allow air and water to flow both in and out, and plant roots and soil organisms to move through the spaces between colloids. Soil OM also allows soils to hold more moisture and provides energy and nutrients (when mineralised) for soil living organisms.

When soils are pugged soil structure is lost, soil density increases and porosity (spaces between soil particles), drainage and aeration decrease. The soil stays wetter for longer, and wet soils are more easily pugged. Soil compaction changes soil properties which can promote greenhouse gas (GHG) emissions, and increases surface water run-off, nutrient loss, earthworm death and anaerobic soil conditions. It also reduces nutrient uptake by plants and root penetration, leading to pasture 'pulling' by grazing animals and increased 'droughtiness' of pasture when the summer/autumn dry arrives.

Of course, it is not only stock that cause soil compaction. Farm machinery on wet soils - such as towing a heavily-laden farm effluent tank over a paddock, ground-spreading fertiliser or even carrying heavy hay and silage bales, or other feed – all cause compaction. The wheel ruts will be slow to recover and, on sloping land, may form channels, increasing soil and effluent runoff to drains or streams.

The introduction of 'Essential Freshwater' regulations attempt to limit pugging damage, especially on winter-grazed crops and are aimed at reducing impacts of sediment, nutrients and excreta on water quality. In some cases, pugging is unavoidable but there is a suite of management methodologies that can be employed to reduce pugging damage and soil compaction (Betteridge et al. 2003).

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Good to excellent management by pastoral farmers in growing productive pasture grazed with livestock in all seasons to return both consumed and uneaten herbage to the soil without causing physical damage, is key to supporting the physical and biological 'health' of the soil and hence providing the best possible growing medium for resilient pastures.

Soil biology (contains excerpts from Sparling 2005)

Without water, and without life, soil is not soil – it is just rock and dust! It is biology that makes soil what it is. We know remarkably little about the biology of soil fauna and flora. Despite being present in huge numbers (a teaspoon of topsoil can have 500 million to a billion bacteria and hundreds of metres of filamentous organisms), for much of the time microbes exist in a "state of readiness", mostly inactive but ready for rapid responses when conditions become favourable. Soil microbes have a slow metabolism and are relatively long-lived, with turnover times in soil ranging between 0.5 and 6 years. They act like this because despite the large amounts of OM in soil, much of it is of poor substrate quality (yields little energy) or is protected by clays and oxide coatings. There is strong competition for the meagre amounts of metabolisable substrates.

Soil is a remarkably hostile place to introduce new micro-organisms. For most soil organisms we cannot modify them directly, instead we alter the soil chemistry (e.g., by adding effluents) and hope the organisms adapt. In general, they do adapt remarkably well, suggesting that most of the necessary organisms are already present in soil – they just need the right selective pressures to develop. Given the complexity of the soil community and the difficulty in introducing new organisms (and it is debatable they are really needed), this is a practical and pragmatic solution to 'using' soil biology.

By any criteria, soil microbes are highly successful. They have huge numbers and mass, more than all other living organisms; they are genetically diverse; survive in extreme environments; show a vast range of metabolic activities and have apparently been around since life began.

Soil biology has a very large role in nutrient cycling (through the decomposition of OM) and transformation in soils, particularly with respect to N, carbon (C) and sulphur (S). Without their activities farmers would need to considerably increase their inputs of brought in nutrients. Pastoral farmers need to keep them housed and fed i.e., maintain soil structure to allow water and air infiltration and produce as much soil OM (food) as possible.

Soil chemistry and fertility

Plants and animal tissues consist of C, hydrogen, oxygen, N and about 14 other mineral elements. Where do these come from? In the case of plants, they come from both the air and soil they grow in, and for animals from the air and the food they consume – in the case of most of our farm animals this is the pastures or crops they eat. Most soils in New Zealand do not contain enough, or all, the essential minerals required for the levels of crop or animal production that most pastoral farmers want. This is where the appropriate application of fertiliser nutrients (or cost-effective sources of nutrients recycled from organic waste materials), which are insufficient or deficient, is important for a resilient pasture system.

The legume, principally white clover, is a very important component in the New Zealand pastoral system. Legumes host bacteria in nodules on their roots that can 'fix' N from the atmosphere into a form used by the legume for protein formation. Grazing animals eat the clover (and associated grasses and herbs) and return a high proportion of N to the soil in dung and urine. Nitrogen is also released in the soil through death and decay of plant material. The N returned to the soil in this way adds to the plant-available N pool and becomes available to the grass in the pasture through the action of micro-organisms in the soil. The application of N fertilisers to grazed pastures will reduce the N-fixing ability of the rhizobia/legume symbiosis.

The one drawback in this relatively natural and organic production system is that the diet of the grazing animal is high in protein-N. In intensive production systems i.e., with high stocking rates, this leads to relatively high amounts of nitrate-N being leached from urine spots of the grazing animal. Much of the current debate around water quality has been driven by the increasing N concentrations, derived from N leached from urine spots, in some receiving waters. Given sufficient phosphate (P), high water temperature and low flow, these circumstances can cause toxic algal blooms and periphyton growth.

Phosphate, potassium (K), S, trace elements and lime are essential for good legume growth and N fixation and therefore pasture production. Soil pH management is also essential to maximise the ability of plants to access both added and inherent soil nutrients. Provision of essential nutrients that are not supplied from soil reserves is usually in the form of fertilisers or other sources of plant available nutrients. In terms of fertiliser nutrients, decades of taxpayer and fertiliser co-operative shareholder money has been spent building up an evidence base which guides the sustainable use of fertiliser nutrients. This follows the "4R principles" of nutrient stewardship i.e., the right rate of the right form, at the right time and in the right place (Johnston & Bruulsema 2014).

The amount of nutrients required on a farm will depend on the soil's stage of development. Large inputs of fertiliser (and often lime), together with the passage of time and recycling of nutrients through the grazing animal, are required to build up soil nutrient reserves and OM content. As soil nutrient status increases, pasture production increases rapidly and this is often referred to as the development phase (Roberts & Morton 2016). In this phase, more fertiliser generally means more pasture, and capital (large) applications of fertiliser will be required for one or more years. Not only will more pasture be grown, but the forage quality of the pasture will improve through the increase in higher fertility requiring grasses, legumes and herbs.

However, eventually, further increases in soil nutrient levels will result in only very small increases in production. At this stage, the optimum soil nutrient status has been achieved and the soil has reached the "maintenance" phase. In this phase, fertiliser is required simply to replace the yearly losses of nutrients from the farm. These losses are in animal products and livestock leaving the farm, dung and urine deposited in yards and sheds, laneways, gateways and around troughs and hedges, plus the inevitable losses which occur from soils (to water and air). The amount of "maintenance" fertiliser required equates to the total of the animal and soil losses.

Maintenance fertiliser rates are determined for each individual farm based on knowledge of the farm's soils, animal production and farm management system (Roberts & Morton 2016). While maintenance rates should be static for a given system and production level, maintenance requirements do change as farm management and production changes. The balancing of nutrient inputs to meet the losses incurred annually can be estimated using a nutrient budget which provides estimates of the fate of plant nutrients for different nutrient inputs and management practices (e.g., stocking rate, supplementary feed inputs).

Nutrient balances are valuable indicators of the long-term sustainability of farm systems. They indicate where inputs of nutrients are inadequate relative to outputs, thereby leading to a decline in the soil nutrient status. Conversely, they can indicate where excessive inputs result in nutrient surplus and give an estimate of potential nutrient losses to the environment. Nutrient budgets also provide a method for comparing nutrient flows associated with different management practices on a farm. High efficiency of nutrient use through conversion into agricultural produce is beneficial for profitable production and to reduce the nutrient surplus or potential for loss into the environment.

Trace elements are present in only very small quantities in the soil making the relationship between soil content, plant, and animal requirements hard to define. However, through a combination of herbage and animal tissue testing farmers can determine what, if any, trace elements are needed for pasture production or animal health. In New Zealand on some soils where the parent material contains insufficient amounts, molybdenum and/or copper would need to be applied for clover production and selenium, copper and/or cobalt for animal health. All of these may be applied as fertiliser nutrients although, in some cases, direct supplementation of the animal is necessary. For other essential trace elements e.g., iron and manganese, we rely on the large amounts present in our geologically young soils to supply plant and animal needs.

The optimum fertiliser strategy for each farm will be unique and should be determined considering the physical attributes of the farm (e.g., soils, topography and grazing management), the financial position of the business (e.g., level of debt servicing, interest rate, and cash flow) and importantly the objectives of the farmer. Ensuring that a farm's soils are at optimal nutrient status supports the ability of pastures to recover from adverse climatic events e.g., drought, more quickly.

Science community

The change in the 1990s to a competitive science funding model, combined with a lack of understanding of the importance of soil science in particular, has seen a major decline in the nutrient management capability and research undertaken by Crown Research Institutes (CRIs) and Universities. Emphasis has migrated to the farm system environmental footprint, in particular N leaching and P loss, and the association between intensity and nutrient loss.

The need for independent soil science expertise is needed more so now than in the past given how influential soil and soil attributes are. In particular, expertise is needed for: (a) managing and understanding nutrient loss; and (b) the allocation and resource management decisions communities are now making to achieve desired water quality outcomes. This independence is critical to support all parties with the same impartial advice on which to make choices and propose equitable solutions.

Fertiliser demand

Fertiliser demand for P has fluctuated as economics and government support have varied (Figures 1 & 2). Current demand has flattened in recent years as soils have reached optimal levels for pasture growth. Nitrogen use has shown strong growth since 1990 as farmers initially used it to tactically aid new pasture establishment and crop growth. Progressively farmers found its use during spring or autumn could extend growth during the cool season. Current use patterns of N fertiliser on dairy farms typically apply following the cows' grazing rotation. This provides the longest spelling period before regrazing, ensuring the pasture

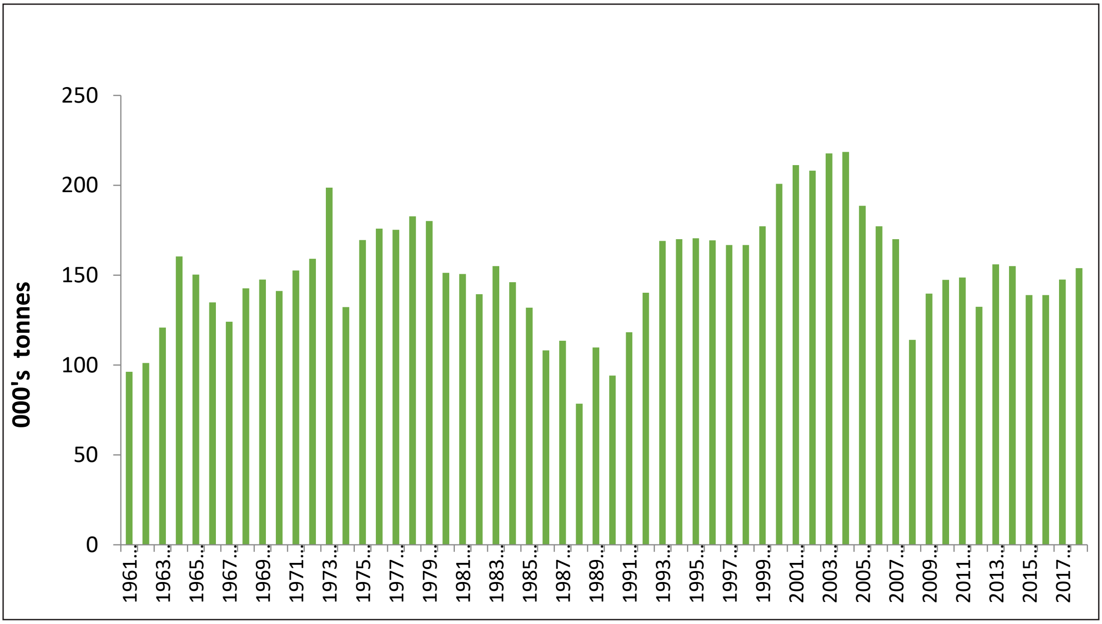

Figure 1 Fertiliser phosphorus consumption in New Zealand 1961-2018 (ktonne/yr).

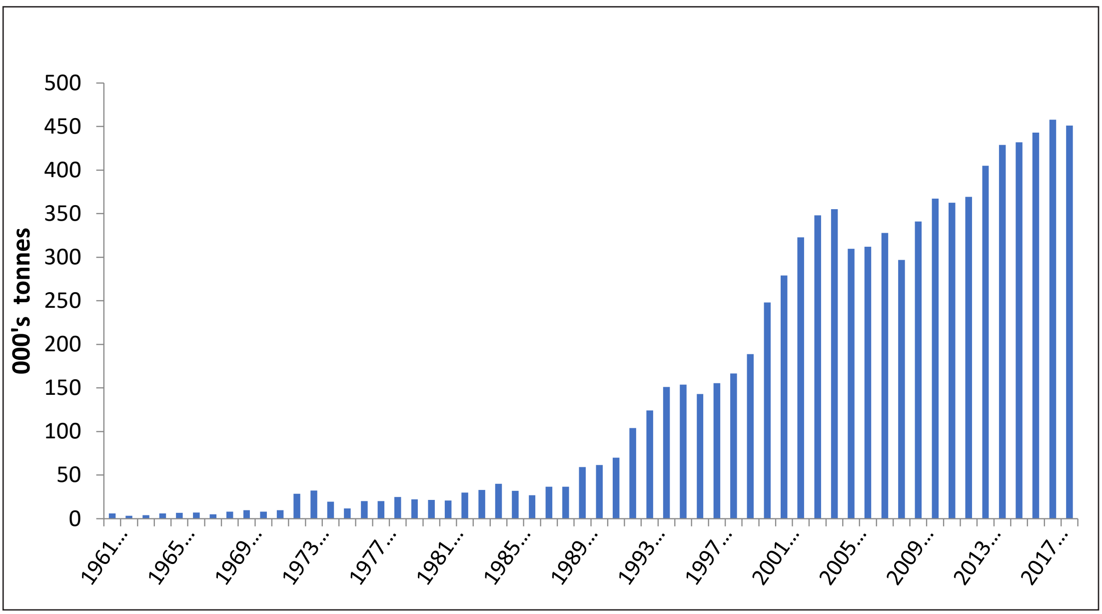

Figure 2 Fertiliser nitrogen consumption in New Zealand 1961-2018 (ktonne/yr).

response to N is highest to gain the best economic response. For dry stock farms N use has lagged due to lower returns per kg of dry matter; use is mainly targeted at crop and specialty areas of the farm with increasing use now in autumn and spring to support feed deficits.

Determining nutrient requirements

Diagnostic tests are a useful source of information to help inform fertiliser policies for pastoral farms. When collected in a planned and regular manner using GPS guidance to retest the same transects at the same time each year, they provide a rich source of historical information on which to base fine-tuning decisions for a fertiliser programme. The standard soil fertility tests such as pH, Olsen P, and tests for S, calcium (Ca), magnesium (Mg) and K are very useful. In conjunction with the scientifically derived information to interpret them (e.g., Edmeades et al. 2005, 2006, 2010), they provide an indication of whether pasture production is being limited by major nutrient deficiencies (and capital fertiliser or lime is required), or whether maintenance fertiliser is all that is necessary to keep perennial pastures growing.

Whole Farm Testing (WFT), whereby every paddock on a farm is soil tested every 5 years, allows identification of paddocks which are below, within and above soil test target ranges. This allows a variable rate nutrient strategy to be developed (Roberts et al. 2010, 2011) which allows every paddock the best chance of recovering from adverse climatic events e.g., drought, and hence be resilient.

New technology in the form of remote sensing will be a near-future development which will reduce the labour requirement of conventional soil and herbage sampling. Measurement of reflectance spectra from herbage and soil, when calibrated against existing soil and herbage nutrient and quality parameters, will enable non-destructive sampling at much finer scale across the landscape. For example, use of a fixed-wing-mounted hyperspectral camera to determine the soil Olsen P status of hill country farms (White et al. 2017) records 10000 observations per hectare (i.e., every 1m^2). These data can then be used to develop a P application plan based on a more comprehensive assessment of soil P fertility than is possible from physically sampling these large properties.

Nutrient requirement models have been produced with the ‘Cornforth and Sinclair’ model (Cornforth & Sinclair 1984) being the forerunner to the Econometric model developed by MAF Research Division for the Fertiliser Association of New Zealand (Metherell et al. 1997) and the latest iteration of OVERSEER FM^{TM}. These decision support software models have been designed to inform the estimation of nutrient requirements for farms incorporating farm physical information with economic returns and farmer objectives.

The advent of GPS/GIS systems has enabled new technology in both ground spread and aerial fertiliser application vehicles to allow for precision application of variable rates of nutrients across varying land areas according to agronomic requirement. Fertiliser application maps can be loaded into the vehicle’s on-board computer system which controls the release rate of the fertiliser being spread. Exclusion zones, such as native bush, open waterways, wetlands and so on are added to the plan so that no fertiliser is applied to unwanted areas. After the spreading event a ”proof of release“ map with the type, rate and date of application can be produced.

Fertiliser advice

In the 1980s the advice for most farmers, given the economics in the post-Rogernomics period, was to apply as much superphosphate as could be afforded. Soil testing was uncommon with fertiliser company representatives nationally totalling approximately 20. Fertiliser advice would often be written on the soil test report sheet or a brief 1-page cover note attached with programmes typically being prepared for a 3-year duration. Today programmes are designed to exploit the on-farm variability with the change simplistically migrating from treating the farm with a single fertiliser programme to breaking the farm up into progressively smaller zones of fertiliser management. Some fertiliser programmes designed by leading practitioners are prescriptive to the paddock or sub-paddock level. This increasingly detailed and site-specific advice or recommendations requires support from many labour-intensive soil sampling transects associated with farm maps and GPS co-ordinates. Of course, the resulting fertiliser programmes result in tailored fertiliser blends or variable rates of application which creates additional workload and expectations from spreaders. Overlaying this has been the need from the Code of Practice to support the use of fertiliser provided so auditability and transparency of the recommendations is possible. This has driven the need for digitalisation of the industry’s fertiliser plans and processes and the provision of online platforms to support the ability of farmers to continue their licence to operate with respect to fertiliser use.

Training and knowledge

Historically, most nutrient specialist’s training was limited to that provided by undergraduate degrees in agricultural science. In more recent years, the tertiary qualifications are more diverse, ranging from environmental management to commerce degrees. The level of detail and robustness of the advice required has also changed, so this level of detail has seen the need for more in-house professional training as the fertiliser and nutrient subject matter expertise has reduced within CRIs and Universities. For the benefit of the wider primary sector, the New Zealand Fertiliser Manufacturers Research Association (FMRA) has established tertiary level short courses to benefit all stakeholders and provide consistent messaging on important nutrient management issues.

Regulation of fertilisers

Fertilisers prior to 1990 were covered by the Fertiliser Act of 1980 which was repealed during the 1990s. The Fertiliser Act covered areas of fertiliser labelling and description, and its repeal left a vacuum that farmers sought to close. In 1992, Federated Farmers, in conjunction with the fertiliser industry, created the Fertmark[TM] scheme. This scheme provided definitions and guidance as to how fertilisers were to be represented, tested, and marketed. This scheme was added to with the creation of the Spreadmark scheme which provides a quality assurance programme for fertiliser application by ground and air. These industry voluntary schemes have been widely supported by fertiliser manufacturers, consultants, regional councils and spreaders since their introduction.

The more profound regulatory change was the introduction of the Resource Management Act (RMA) in 1991. This Act in practice implied fertilisers were contaminants and therefore fertiliser use would require a consent unless permitted within regional council plans. This led to the FMRA producing the Fertiliser Code of Practice in 1996 and successfully advocating for its inclusion within regional plans. As expectations of fertiliser and nutrient management have become tighter the Code has been revised twice (and now renamed the Nutrient Management Code of Practice), recognising that for dairy farms in particular the management of nutrients should consider effluent in addition to manufactured fertilisers.

The year 2003 marked the introduction of N and P caps in the Rotorua Lakes area by Environment Bay of Plenty, which was followed by the N cap in the Lake Taupo catchment by Environment Waikato. In principle, the nature of the rules was supported on the basis that they were output based rather input controls. However, they were opposed vigorously as the implementation imposed significant new constraints on farmers, their activities on the land and consequently the value of that land.

In 2005, due to non-governmental public pressure and the increasing threat of further local and central government water quality regulation, the dairy industry responded with the negotiation of the Clean Streams Accord. This Accord set a target for the wide adoption of nutrient budgets developed using the OVERSEER model as described earlier. This drove farmer recognition of the significant source of N and K that dairy effluent contained and saw effluent being utilised more efficiently, for example displacing fertiliser use from areas where effluent was regularly applied.

The Clean Streams Accord brought significant focus on nutrient losses and management and in particular scepticism of the industry driven data and outputs of the Accord. The fertiliser industry recognised the need for auditing staff recommendations, accreditation, and the highly skilled nature of the industry's nutrient specialists. Funding was provided by FMRA to establish the Intermediate Sustainable Nutrient Management Certificate at Massey University which in recent years has been extended to include an advanced course, a GHG module and the Intermediate Farm Environmental Planning (FEP) course. The recognition by the wider industry for competent use of OVERSEER and nutrient management advice led to the Certified Nutrient Management Advisor (CNMA) scheme. More than 300 advisors are now certified adding significantly to the professionalism and credibility of those working in nutrient management.

The implementation of output-based regulation, where the impact or losses of the farm are regulated rather than the activities that a farm can undertake, necessitates that the externality of e.g., N, P or sediment is either measured or modelled to quantify the losses. To date the impracticality of measuring nutrient losses in a regulatory context has led to the adoption of OVERSEER in regional plans. This use of OVERSEER in a regulatory context is hotly debated and the outcome of its use or substitution with another mechanism will have significant impacts on how on-farm reporting and nutrient management are undertaken.

The 2020 year was a watershed year for water quality nationwide with the National Environmental Standards (NES) and National Policy Statements (NPS) for freshwater being introduced. The NES introduced a cap for N fertiliser use at 190 kg N/ha/yr for grazed pasture. This cap will impact dairy farms and especially in the newer dairying areas like Canterbury and Southland where soil N status is lower. This N fertiliser cap is expected to result in an accelerated adoption of more efficient N fertiliser forms e.g., urease inhibitor coated urea.

Climate change policy will also impact fertiliser use as fertiliser N contributes approximately 3% of New Zealand's agricultural emissions. Over 50% of urea fertiliser sold is treated with urease inhibitors which halve direct ammonia losses but only contribute to a very small reduction in direct nitrous oxide (N_2O) emissions. With the inability to use dicyandiamide (DCD), a common nitrification inhibitor, because of historic detection of trace residues in milk, the need remains for finding a nitrification inhibitor that is acceptable to both regulators and primary producers, that specifically targets and reduces N_2O (with a reduction in nitrate leaching as a co-benefit).

Regional council plans

Regional Councils issue plans with objective targets and outcomes for achieving community values for water quality and quantity. The first generation of these plans was relatively permissive, but more recent iterations have become progressively more prescriptive. The introduction of these regional plans, as a requirement of the RMA, created a whole new landscape in the context where farm activities were more controlled. Consequently, the first of these plans were subject to strong advocacy, debate and submissions as the precedents and principles for rules and regulations were established. Processes are more collaborative today, but the element of resource allocation continues to be strongly contested as the detail of allocation is decided. One of the consequences for the fertiliser industry is ensuring we resource and strive for farm plans that are implementable. Given the industry's historic investment in OVERSEER the fertiliser companies and FANZ continue to advocate for output-based regulatory frameworks. These output frameworks support the investments that companies have to make to develop products and services which can modify the nutrient footprint on farms e.g., urease inhibitors, low P-solubility fertilisers and decision support tools.

A major challenge with most regional plans is the timelines by which farmers/growers require a nutrient plan. These timelines fail to firstly recognise the low capacity of the nutrient advisors to satisfy the need and secondly do not provide certainty for the ongoing requirement and content of these nutrient plans. These failures undermine the confidence people need to see to create a career in the farm planning space. Addressing these failures is critical to building capacity and experience.

Unintended consequences of fertiliser use

Despite all the science and its careful but pragmatic application on New Zealand pastoral farms, there are unintended consequences when using some fertiliser nutrient sources. For example, there are unnecessary and indeed unwanted elements in the P rocks used to manufacture P fertiliser around the world. One such element, cadmium (Cd) has created elevated legacy Cd levels on soils where historically regular amounts of superphosphate, manufactured from Nauru Island P rock, have been applied to overcome P deficiency. These legacy areas are mainly in the Waikato, Bay of Plenty and Taranaki regions (Abraham et al. 2016) where dairy farming on volcanic soils has been practised for over 100 years. However, a multi stakeholder Cadmium Management Group (Rys 2020) was formed in 2011 to ensure the on-going management of the Cd issues and support the fertiliser industry's voluntary Cd reduction policy and the tiered fertiliser management strategy (Sneath 2020).

The use of N fertilisers has been credited with supporting 50% of the current world population. However, plant available N forms such as ammonium and nitrate ions are relatively mobile in soil and when soils drain the drainage water can remove surplus available N predominantly by leaching. This leached N is mostly from mineralised soil N surplus to plant uptake or is derived from the urine patches (Di & Cameron 2005) of grazing animals (eating protein rich grass/legume pastures and other forage). When N fertiliser is applied using the 4R principles, direct losses of N from N fertiliser are relatively low (i.e., $\leq$10%). New products based on urea, the most used N fertiliser in pastoral systems, have been developed to help increase N use efficiency. Gaseous losses of N (ammonia volatilisation) immediately after urea application have been shown to average around 15% and range between 7% and 20% (Bishop & Manning 2011). A urease inhibitor, N-[n-butyl] thiophosphoric triamide (NBPT), coated onto urea fertiliser has been shown to decrease ammonia volatilisation from urea fertiliser (Watson 2000) by an average of 50% in New Zealand pastoral conditions (Sherlock et al. 2011; Zaman et al. 2008). SustaiN and N Protect are urease inhibitor-coated urea fertilisers produced by the New Zealand fertiliser co-operatives for their customers.

Nitrification inhibitors are also coated on N fertiliser products. This results in less risk of direct leaching of nitrate-N originating from the added N fertiliser. The nitrification inhibitor, DCD, has been coated on N fertiliser in other countries for decades and work in the early 2000s by Lincoln University researchers (e.g., Di & Cameron 2005) showed good efficacy in reducing N leaching from urine patches (indirect loss of N).

The future

One of the most profound changes has been the progressive recognition and increasing importance of climate change in terms of weather/climate variability now and into the future. The primary sector and the fertiliser industry's social licence to operate will be impacted by our international customers' expectations as much as domestic politics regarding on farm and sector practices. There will also be a need to reconsider nutrient management in terms of how climate change impacts farm systems, the crops grown, the year-to-year variability – perhaps leading to more tactical just-in-time fertilisation combined with lower base fertility on farm. In addition, the forms of nutrients will need to be considered given rainfall events are forecast to become more intense and dry periods longer resulting in a greater proportion of nutrient losses occurring from single events.

The future for fertiliser N use will be determined by firstly how responsible our stewardship of the product use is and secondly how holistically N's impacts are considered in terms of equivalence between the impact of fertiliser N and imported feed sources. Certainly the 190 kg N/ha/yr rule will drive farmers towards more efficient N fertiliser forms such as those with urease inhibitors. The current absence of a nitrification inhibitor is one that should be addressed as society will need to accept some degree of risk from its use and risk of food residues as a trade-off for lower emissions whilst at the same time protecting the agricultural productivity and economic prosperity N fertilisers provide.

Finally, the risk of running out of P resources (i.e., the 'peak' P concept) is often cited as occurring within several decades but the reality is that, assuming geopolitics do not prevent physical access to these reserves, deposits throughout North Africa are sufficient to meet world demand for several centuries. The unforeseen risk lies with S which in many cases is derived from fossil fuel refining and use. The decarbonisation of economies and reduced fossil fuel use will restrict the supply of S. Sulphur and sulphuric acid are the feedstock for superphosphate production, and sulphuric acid is used in the first step of many industrial processes including the production of other acids such as phosphoric acid. Agriculture depends on the supply of plant available S for our clover growth and so within a few decades the fertiliser industry may be considered more as a 'S industry' than a 'P industry', recognising their dual importance for pastures.

Conclusion

Over the last 30 years the fundamental soil science, soil testing and fertiliser products have largely stayed the same. The changes that have been described were driven firstly by increasing expectations of the farmer/grower to improve cost effectiveness of fertiliser, hence more testing and operating at finer scales as technology allowed. Secondly, the increased regulatory, societal and consumer expectations on the impact of fertilisers and farming on water and our wider environment has led to the development of fertilisers and advisory tools with features that mitigate or reduce these impacts. These drivers of our industry will continue to drive change and innovation along these same paths.

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