

The role of technology transfer to improve fertiliser use efficiency

Miles Grafton · Ian Yule

Received: 12 January 2015 / Accepted: 12 February 2015 / Published online: 16 March 2015
© Springer Science+Business Media Dordrecht and International Society for Plant Pathology 2015

Abstract Over the past 80 years, crop yields under developed agriculture have increased rapidly. However, in many countries the rate of increase has slowed significantly. In some areas of the world such as Europe, nutrient inputs have been significantly reduced and yields have stagnated, while in other parts of the world the amount of nutrients applied have been constant with moderate yield increases. In either case, farmers are seeking to improve nutrient use efficiency. The potential to increase yields is significant. The greatest potential exists in areas where yields are low and limited by a readily remedied limiting factor; a situation often encountered in developing nations where nutrient deficiencies persist. Yield response to nutrient application where no other limiting factor exists, is invariably a diminishing return curve, showing strong increases in yield with initial additions of nutrients then plateauing with increasing applications. Remote sensing by satellite and wireless communications offer an opportunity to identify limiting factors in crops globally and provide timely management information to farm managers to control inputs or adjust practices. In the developing world, the use of remote sensed data may be a required focus area, where services are provided and information dispersed, to assist farmers. For example climate and surface temperature monitoring could improve fertiliser efficacy by scheduling applications when soil moisture conditions allow uptake of nutrient,

whilst also preventing applications prior to deluges, which would cause fertiliser run off to waterways. This paper explores the use of remote sensing technologies to improve efficiency of fertiliser use.

Keywords Remote sensing · Nutrient management budget · Nutrient losses

Introduction

Farmers the world over need to make better informed decisions. In first world agriculture, much of that better information has come from physical sampling of the soil or plant, but the reality for many is that this process is simply not available because there is no testing infrastructure, or that it is too costly to implement on a large scale. In this case remote sensing could offer a disruptive technology that would circumvent the need for large scale sampling. The technology is practical and capable of generating information that would assist growers. Therefore, where it is relevant but not available it should be introduced as soon as possible.

Remote and proximal crop sensing undertaken by various means, to measure plant nutrient status has tended to focus on the efficient use of nitrogen. This focus has come from a perspective of yield maximisation and increasing nutrient use efficiency. The main reason is that the type of sensors used to-date have limited scope, being only able to recognise differences in chlorophyll levels in the plant and therefore can only estimate nitrogen concentration. If more sophisticated sensors could be used, the presence of other nutrients and their concentration could be estimated. Case study evidence from New Zealand suggests that considerable savings can be made, either by reducing nutrient inputs on areas with luxury levels

The authors are currently engaged with industry and Government in joint funded research in applying the principles of remote sensing and nutrient targeting in hill country farming systems of New Zealand, which is funded by Ravensdown Fertiliser Co-op Ltd and the New Zealand Ministry of Primary Industries, (MPI).

M. Grafton (✉) · I. Yule
New Zealand Centre for Precision Agriculture, Massey University,
Palmerston North, New Zealand
e-mail: m.grafton@massey.ac.nz

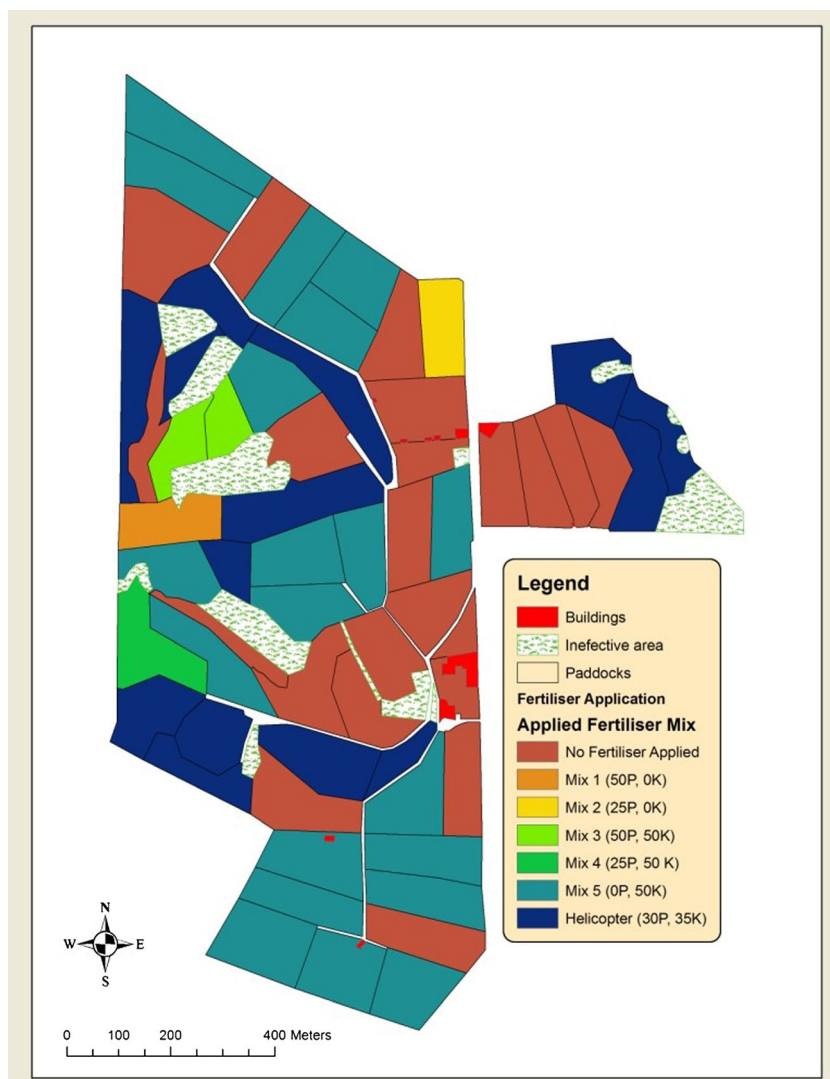
of soil nutrients, or better targeting of nutrient input to areas where nutrient deficiency is recognized as the limiting factor. Remote sensing of crop nutrient status would allow scheduling of correct fertiliser applications and thereby optimize economic output. The object of this paper is to explore remote sensing of plant nutrient status and illustrate its application in agriculture using two New Zealand case studies.

Dairy case study

Dairy production is based around an intensive pasture production system, with rotational grazing, where there has been considerable interest in controlling nitrogen inputs in recent years. Ironically, it is perhaps with the other major nutrients that the most significant increases in efficiency of use and reduction of costs can be achieved. Most dairy farms in New Zealand run a rotational grazing system, where large herds of cows are moved to fresh grazing on a daily or half-daily basis.

Farms typically have a large number of small paddocks to control this grazing system. The traditional sampling approach has been to take an average value from 6 to 9 soil samples for the whole farm on which to make fertiliser recommendations. Each major nutrient has an optimum range within the soil, which is considered non-limiting to plant growth. As an example, the authors have data (Pers. Comm. Michael Manning, General Manager Research and Development, Ravensdown Fertiliser Cooperative NZ) where an approach of all paddock sampling has been taken. Composite soil samples are taken from each paddock; typically paddocks are 1 to 2 ha in size, depending on herd size and known variation in production systems. Although there has been a considerable increase in cost to do this, NZ\$35/ha (approx.), the evidence is that larger savings in fertiliser can be achieved, along with better-targeted fertiliser application to address deficiencies. An example of 9000 samples showed that 25 % of the area had Olsen P levels over the optimum range, 17 % was within optimum range and 58 % were below optimum range. The result is that fertiliser

Fig. 1 Nairuo Dairy farm, Taranaki, New Zealand, H & A Lawrence, showing where different amounts of phosphorous and potassium were applied after a whole paddock soil survey was conducted in 2010



can be directed away from the super-optimal areas to the sub-optimal. In some cases where high levels of fertiliser have been applied, savings of approximately NZ\$150 per ha over the whole farm have been achieved - around 40 % of base fertiliser costs (Yule and Grafton 2010). Other dairy farmers (MacKenzie 2013) have achieved similar and, in some cases, greater savings

Dr. Hayden Lawrence, using whole farm soil testing on his dairy farm, identified areas, which did not require any fertiliser, allowing mining of fertility on the family dairy farm from these areas. In other zones targeted application of nutrient was applied to support optimum economic production (Figure 1) In year 1 of this régime he saved NZ\$305 ha⁻¹ in fertiliser cost and grew about 1 tonne ha⁻¹ more dry matter.

Other findings

Haag (2014) observed similar spatial variation in soil nutrient effects from uniform fertiliser application, where an area of historically lower yield had higher levels of soil nutrient present, presumably through lower levels of crop removal over a number of seasons. Environmental variables within the farm, such as soil type and texture, which can influence moisture holding capacity and crop growth, meant that uniform applications of fertiliser could lead to spatial variation in soil nutrient levels within a paddock and farm. The additional cost in soil sampling has been justified, but it is also possible because individual farmers have had the wherewithal to carry it out. This may not be the case where there are more limited financial resources.

Crop sensing using hyper-spectral and multispectral proximal and remote sensors has been developing over the last 20 years. Multi spectral sensors, sense light from a few discrete wave length band widths in the near infra red and red edge regions of the spectrum which can give a good indication of changes in crop appearance from which quality indices have been devised. Hyper-spectral sensors differentiate a continuous range of band widths over two thousand wave lengths from which plant nutrient status is starting to be derived.

Researchers such as Pullanagari et al. (2012 and 2013) have successfully estimated pasture quality indices, nutrient and energy status as well as dry matter. They also monitored crop growth rates, plant health and disease and predicted yields with a high degree of statistical significance (Solari et al. 2008; and Starks et al. 2008). A range of multispectral sensors has been used and these have most sensitivity to variation in chlorophyll content and biomass. If individual plant nutrient concentrations and quality parameters were required then the spectral range and resolution would need to be expanded and improved (Holland

et al. 2012). This is because the limited number of bands received by multispectral sensors limits the information to providing indices. Hyper-spectral sensors provide the opportunity to provide further information by using advanced statistical methods such as partial least square regression, neural networks, kernel learning and supported vector machines to match the wave bands from large data sets to predict mineral content in vegetation.

In terms of improving the efficiency of fertiliser use and increasing yields to feed the projected 9 billion by 2050, monitoring climate, soil moisture status and major nutrient deficiency from satellite mounted sensors, in space would be the most efficient means of acquiring farm management information. This could be undertaken automatically and information supplied remotely in order to control the quantity and timing of fertiliser inputs in the developing world (Kuri et al. 2014). However, this would require that appropriate fertilisers are available and a management information system is in place to disseminate the data. At present, hyperspectral remote sensing equipment, such as the Aisa Fenix weighs 70 kg and is too heavy for economic transport into space, but remote sensing of crop nutrient status from aircraft, using an Aisa Fenix sensor (Specim, Oulu Finland), has been undertaken by the authors' team with some initial success. In the future the number of satellites monitoring agriculture and the sophistication of the equipment carried will improve, which will allow near real time monitoring of agricultural crops on a global scale.

Can technologies, such as remote sensing, be used by farmers in the developing world in order to achieve fertiliser efficiency gains? Is it possible to use these technologies to identify other limiting factors and improve crop protection from pests and diseases using available resources? Achieving these aims would dramatically improve yields.

In the developed world high resolution (approximately 2 m) proximal sensing using hyper-spectral and multispectral sensors is now being used to measure quality parameters. Some of these are pasture growth rates (Rahman et al. 2014) and nutrient use efficiency as a function of rainfall. Moreover, useful information such as predicting crop yield in developing corn (*Zea mays*) is possible (Torino et al. 2014).

Similar methods are being used to glean information remotely from satellite-mounted sensors orbiting the earth. The number of satellites, frequency of passes, the resolution of images and the number of spectral bands being sensed are increasing. Some satellite sensor imagery such as MODIS, ASTER, SPOT and Landsat information is processed, orthorectified and made available free of charge. It is possible to obtain information such as vegetative indices, for example the normalised digital vegetative index (NDVI). NDVI is a ratio obtained by comparing the relationship between a near infrared (NIR) wave band and a red wave band (R), where higher

ratios indicate healthier plants with deeper green hues and nitrogen content.

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \quad (1)$$

An example of an NDVI map derived from satellite imagery is presented in Figure 2.

The frequency of passes and the number of available spectral bands indicates that these sensors are more suited to monitor trends, such as moisture deficiency and crop health at greater than 30 m resolution every few weeks depending on cloud cover. Xingha et al. (2014) successfully predicted surface temperatures using Fourier transform and Krig modelling as a basis for dictionary learning from previous cloud free data. In the future, these methods could be employed to model crop health or moisture stress. Superior higher spatial and spectral resolution imagery such as QuickBird and RapidEye, which are commercially available, could provide better resolution information more frequently. However, using data from these sensors in developing nations may require some centralised funding aid as the proposed end users are unlikely to be able to fund acquisition of the data.

Global fertiliser use

When considering feeding more than 9 billion people by 2050, fertiliser use must be viewed at the global level. Fertiliser inputs, other than natural manures, began in 1840 when Justus Von Liebig demonstrated improved plant growth

from inputs of nitrogen (N), phosphorous (P) and potassium (K) (Mersmann et al. 2013). Fertiliser manufacturing and use received a boost in 1910 with the invention of the Haber-Bosch process of manufacturing ammonia. Since then the use of fertilisers has steadily increased. World inputs of N, P and K has increased from 90 million tonnes in 1980 to slightly over 143 million tonnes by 2013 (Cooke 1982; and Heffer 2013). Currently, around 104 million tonnes of nitrogen is applied, 17 million tonnes of phosphorous in approximately 40 million tonnes of phosphate, and 22 million tonnes of potassium in 27 million tonnes of potassic fertilisers.

Fertilisers are a major contributor of agricultural nutrient inputs, but must be seen in the context of the global nutrient cycle. As yields increase, losses from the system increase as nutrients are removed in crop product (Anon 2014). For the maintenance of sustainable yields, nutrient additions from fertiliser applications, atmospheric nitrogen fixation and mineralization must be equal to the total losses from the farming system, whether these are from crop product, leaching or immobilization. Atmospheric losses of nitrogenous fertilisers as nitrous oxide, dinitrogen or ammonia must also be considered.

In the developed world, fertiliser application is generally at the economic optimum with nutrient inputs at the plateau point of the response curve. However, in many countries, inputs are restricted to reduce run-off and leaching while precision agricultural techniques are being used to map yields, soil texture, soil moisture content, nutrient status of soils and plant tissues. From this spatial information, a nutrient management plan is often developed, part of which encompasses the precise placement of fertiliser and measurement of effluent in order to maximise the benefits to the crop and minimise

Fig. 2 NDVI image of Erewhon Station (30 m resolution) in New Zealand: higher readings indicate better pasture quality. Image based on data acquired courtesy of NASA from Landsat 8 satellite

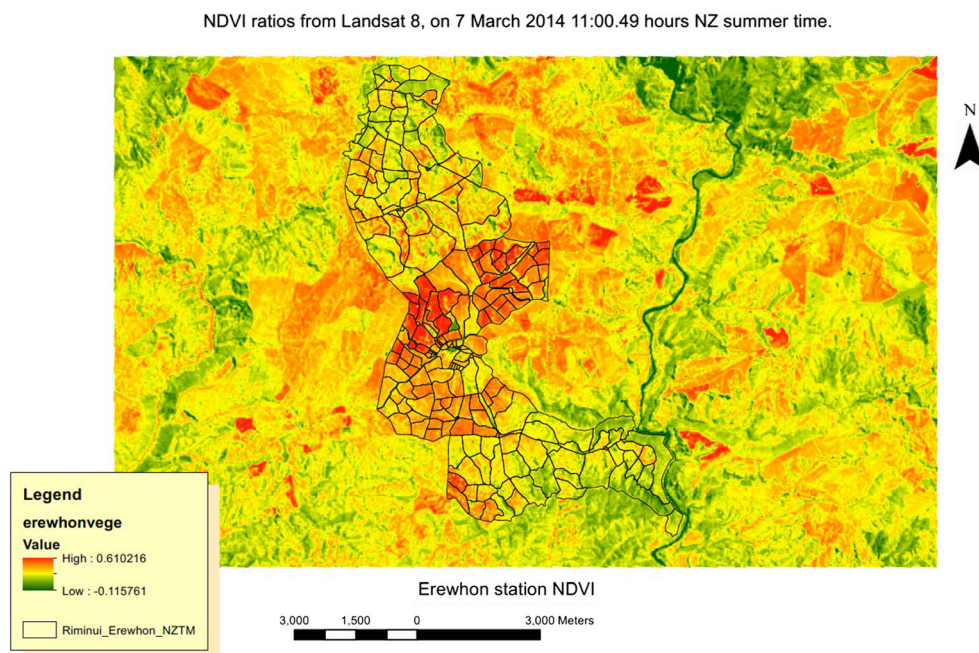


Table 1 Estimate of global agricultural nutrient budget for 2013 adapted from Cooke (1982)

Nutrient (million tonnes)	N	P	K
<i>Inputs</i>			
Natural Fixation			
Arable	50		
Grassland	100		
Fertiliser	104	17	22
Mineralisation		10	150
<i>Recycled</i>			
Animal Wastes	8	17	120
<i>Outputs</i>			
Leaching	20	2	80
Immobilisation/absorption	60	25	
Lost as ammonia	30		
Denitrification, nitrogen and nitrous oxide	60		
Crops	75		75
Grassland	15		140

environmental risks through leaching and runoff. All of these techniques rely on information from spatial data, which allow better decision-making and result in better yields from the more efficient use of fertiliser. For an estimation of the global agricultural nutrient budget, see Table 1.

In the developing world, increased use of fertilisers should produce large increases in yield. For example many parts of Africa, Asia and Latin America are potassium deficient and yield increases of 240 % have been achieved by application of 125 kg.ha⁻¹ KCl (Fageria et al. 2011).

A New Zealand case study

Materials and methods

Sheep and Beef NZ report that the average sheep and beef farm carries 9.4 stock units per hectare and applies 10.4 kg of fertiliser per stock unit (Anon. NZM&W. 2010). This equates to 97.9 kg of fertiliser being applied per hectare, although there is no break down into individual fertiliser components. The nutrient budget

Table 2 Nutrients removed g kg⁻¹ live weight and g kg⁻¹ greasy wool from Jarvis et al. (2002)

	N	P	K	S	Ca	Live weight Conversion %
Sheep	13.0	6.0	2.0	0.8	13.4	48
Lamb	13.0	6.0	2.0	0.8	13.4	45
Wool	150.0	0.2	17.0	34.0	1.5	

Table 3 Indicative nutrient budget for 9.4 sheep stock units per hectare

	N	P	K	S	Ca
Sheep kg Nutrient	1.99	.92	.31	.12	2.05
Lamb kg Nutrient	3.27	1.51	.51	.20	
Wool kg Nutrient	6.34	.01	.72	1.44	.06
Leaching / run off	12.00	1.00	52.00	39.00	33.00
Atmospheric	17.00				
Immobilisation /Absorption	38.00	18.00			
Total Nutrient	78.60	21.44	53.54	40.76	38.47

requirement of a typical farm stocking 9.4 stock units (SU) per hectare is known. The amount of nutrient removed per kilogram of animal product in an all sheep system is shown in Table 2. Therefore, after farm losses to the environment, the net amount of nutrient applied must at least balance that removed by the sale of animals, to prevent fertility being reduced.

The nutrient removed can be calculated for a farm stocking at 9.4 SU and fed into a nutrient budget. A typical budget is shown in Table 3, assuming an average ewe carcass weight of 26 kg and lamb carcass weight of 15 kg with 4.5 kg wool off each animal.

The nutrient lost from the farm system can be matched with a fertiliser recommendation to maintain fertility. For the example in Table 3, it is assumed that farm fertility is quite good and that there is enough clover present to fix 60 kg of nitrogen per hectare. In farm situations with low fertility, applying less than 20 kg phosphorous as phosphate per hectare, or in low rainfall areas where the amount of nitrogen being fixed will be less than 60 kg per hectare (Wan et al. 2009), more fertiliser will need to be applied to balance the nutrient budget. It is also assumed that there is no requirement for potassium as there is enough clay to provide an adequate supply that may be mined.

To balance the nutrient budget, 277 kg of Sulphur Super 15 (8.7 % P, 14.7 % S, 19 % Ca) and 40 kg of urea (46 % N) would be required. Given the assumption of reasonable nitrogen fixation, around 315 kg of fertiliser is required per hectare, or 33 kg per SU. Therefore, the usage as of 2010 of 10.4 kg of fertiliser per stock unit was inadequate in the sheep and beef farm sector to maintain fertility.

There can be little doubt that the sheep and beef sector cannot continue to mine fertility for any length of time without a drop in production through a reduction in stock carrying capacity. Scott et al. (2006) demonstrated that farmers are better off applying a low quantity (30 to 38 %) of fertiliser annually rather than applying the same amount in one application every 4 years. Thus, those farmers who maintain some application of fertiliser continuously are better off than those

who stop fertilising when prices are high, or produce prices are low, with the intention of making it up with a larger application, when prices are more favourable.

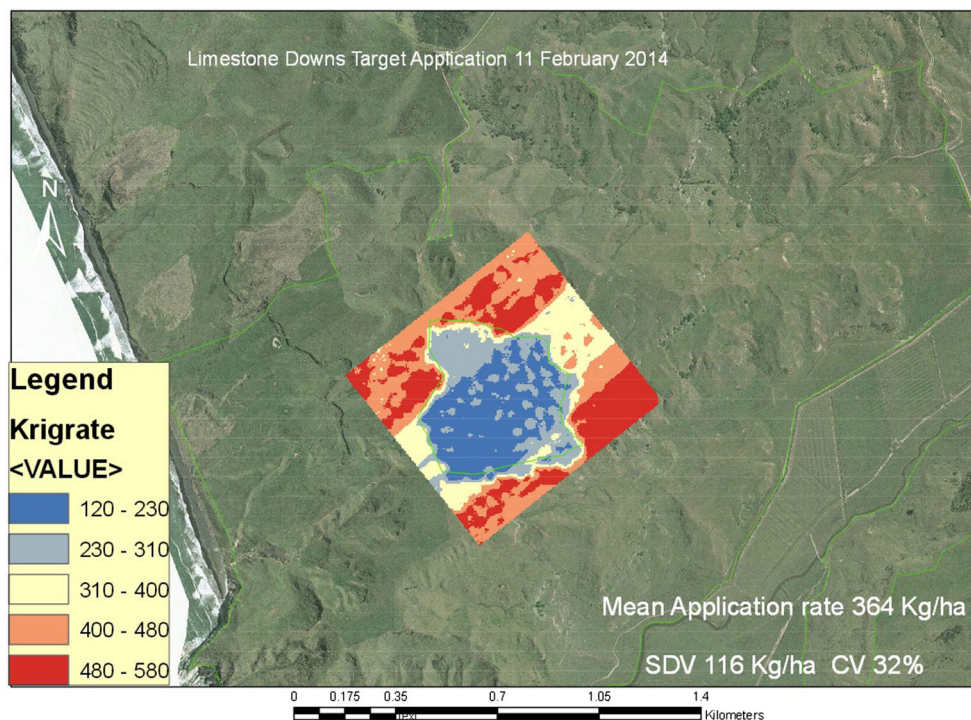
It is inevitable that unless fertiliser application rates increase on hill country farms, low fertility species will dominate and the presence of legumes efficient in nitrogen fixation will diminish, accentuating the problem. This issue may affect stock condition as phosphate is a component of nucleic acids and nitrogen and sulphur are components of protein. For example, crude protein is measured in plant material by obtaining the proportion of nitrogen and multiplying this by 6.25 as protein is generally 16 % nitrogen.

The pioneering to precision project

The authors are engaged in developing a disruptive technology around remote sensing. It is well recognised that much of the New Zealand hill country which supports most of the country's beef and sheep production is nutrient deficient, and it is intended that remote sensing will allow farmers to target the application of nutrients to a much finer resolution. The Pioneering to Precision Project involves the use of hyperspectral airborne sensing to guide and inform fertiliser application and applies the same basic principles as the dairy example, but the spatial resolution is much finer, the areas covered are much larger and the delivery technology is also different.

The research partners have also developed a computer controlled aerial application system for a topdressing aircraft that can deliver fertiliser accurately to ensure the right product is applied at the right rate in the right location. Each plane is capable of spreading 300 tonnes of fertiliser per day covering an area of up to 1200 ha in rolling and hill country. Historically aircraft have given very variable spreading. Boundary detection was done visually by the pilot, who is already busy trying to fly an aircraft at low altitude, and then has to activate a large lever to operate the hopper door. Aircraft speed varies considerably and the only mechanism to achieve an even application rate is through adjustment of the hopper door opening, which is nearly impossible for the pilot to achieve manually. However, with a computer control system carrying out this function the level of variation in spread was reduced by half (Grafton et al. 2013). Due to this technical innovation, aerial topdressing can deliver a much more precise application of fertilizer, making the idea of variable rate or targeted application viable. Figure 3 shows a map of a computer controlled aerial application over a 70 ha test area conducted over Limestone Downs, a farm in the North of New Zealand. The aim was to deliver two rates, 250Kgha^{-1} over 25 ha, and 500Kgha^{-1} elsewhere, of single superphosphate and measure the system's ability to achieve this in terms of the coefficient of variation (CV; standard deviation of the spread divided by the mean, expressed as a percentage). The CV of the same aircraft with the same pilot using a manual system was

Fig. 3 A Krig map of an application of single superphosphate at two target rates on Limestone Downs using computerised spreading control. The inner blue enclave area had a targeted rate of 250Kgha^{-1} , the rest of the block had a target rate of 500Kgha^{-1} . The area is 70 ha and the map represents 4500 points taken from the aircraft delivery rate. The area was ground proofed using 151, 0.5 m^2 collector cones. The variogram from the aircraft accounted for 99.9 % of variance, whilst the variogram from the collectors accounted for 91.9 % of the variance



previously measured at between 40 and 90 % on the same farm whilst only applying one rate.

The hyperspectral (about 2400 spectral wave bands, VIS, NIV and SWIR regions of the spectra) research undertaken in the Pioneering to Precision programme has shown promise in identifying statistical methods of correlating individual minerals in plant tissue by wet chemistry analysis. Good correlations of 0.7 or better have been obtained in estimating nitrogen, phosphorous, sulphur, potassium and calcium. Similar results have also been obtained for plant quality indices, metabolisable energy (ME) and dry matter percentage (DM). These results have shown robustness as the same correlations have been found at two different pasture production locations 300Km apart.

Discussion

Effects on a global scale

The potential exists of using remote sensing to detect nutrient deficiency and other limiting factors from space. When combined with the availability of fertilisers and means of applying them accurately there is massive potential for increased crop yields and reducing nutrient losses to the environment, as pollutants in waterways and by volatilization as greenhouse gas emissions.

At present, remote sensing by satellite is limited to multi-spectral analysis (about 12 bands). This limitation is due to weight restrictions of instruments able to be launched into space for long monitoring periods. However, these bands are able to provide enough information to monitor crop health, weather systems, moisture deficiency and environmental or land use change.

Satellite based technology is developing as spectral resolution and the number of bands available has increased as well as spatial resolution. Thermal imaging may aid the production of plant development models and yield mapping by providing a better spatial understanding of surface temperature and soil moisture in the environment.

The number of satellites is soon to increase rapidly with the development and deployment of cubesats, small satellite vehicles which can be easily launched. The company Planet Labs is in the process of launching a constellation of 28 cube satellites of which 16 were launched from the International space station in February 2014. They are known as Flock and are about the size of a shoebox. Each one will be used to take repeated photographs of the earth. When combined with other developments, such as SkyLab Imaging, sold to Google for \$500 M, <http://www.skyboximaging.com/>, these will reduce the cost of obtaining commercial imagery from

space dramatically and images will be available in a much shorter time frame.

In the near future, remote sensing of zones or regions of interest will be possible. Satellite sensing of crop health, moisture deficiency and short to long-term weather systems will be possible. Assuming moisture or temperature are not the limiting factors to production or predicted production, then further investigation could be undertaken, using hyperspectral sensors flown by aircraft, to determine factors in terms of mineral deficiency that may be limiting the potential economic yield. Such deficiencies could then be remedied through precision application of the required fertilisers.

Co-coordinating fertiliser inputs with soil moisture balance, assisted by remote sensed climate data can further optimise fertiliser efficacy. Moisture deficiency has a higher order impact than fertiliser and, therefore, impacts on yield more than fertiliser (Bretherton 2012; and Kuri et al. 2014). Timing of fertiliser applications and their frequency to avoid run off can improve fertiliser efficiency by reducing waste and ensuring metabolism of the fertiliser applied. Frequent small applications made when growing conditions are optimal are more efficient than large infrequent applications.

Effect on global fertiliser use

Remote sensing of major plant minerals in crops opens the potential to apply only those inputs that are required to rectify mineral deficiencies or increase economic crop yields. The effect is likely to be improved efficiency of fertiliser use and probable increases in yields and production without the need to increase fertiliser application.

It may also be possible to find areas where yields are low and nutrient deficiencies are not present. These areas are present in many farm environments and occur when nutrients are present or are applied in greater amounts than can be metabolised by the crop. In these areas, fertiliser may be withheld so that the nutrient present can be mined and fertiliser only applied to zones where it may be of economic benefit.

Conclusion

Precision agriculture tools are enabling variability in agricultural production systems to be exploited. One of the main tools being employed is mapping areas in terms of fertility and yield. In conjunction with variable fertiliser delivery systems, improved efficacy of farm fertiliser inputs and economic benefits have been achieved.

This paper has not examined food production yield by crop, and the effects of crop choices on fertiliser inputs.

This will likely be an issue as the world population places increased pressure on food production. Necessity may mean that grain crops be replaced by higher yielding root vegetable crops that have a higher percentage of edible material per total plant mass. Such changes to crop production are not unprecedented and, for example, occurred with the introduction of the potato from the Americas to Europe in the sixteenth century.

There has been a rapid increase in the number of proximal and remote environmental sensors available. Improvements in miniaturization of sensing tools has led to a large increase in numbers of remote piloted aircraft systems used to monitor agriculture. It is also leading to a rapid deployment of small satellites, which are being launched into space. There will be a plethora of data available which could assist in crop monitoring. However, there will also need to be systems in place to process and disseminate this information in a useful and timely way to assist farmers with the types, quantities and timing of their fertiliser applications.

Automation of data processing of proximal and remote sensed information is occurring. Software programmes such as ENVI (Excelis Visual Information Solutions, Denver Co.) and ArcGIS (ESRI, Redlands Ca.) provide processing, data interoperability, tool building and scripting ability. Agricultural mapping services, using these tools, are provided by some operators. Some manufacturers of agricultural machinery, guidance technology, and remote piloted aircraft systems (RPAS), provide automated software that produce specific maps for the users of their machines. Manufacturers of agricultural machinery are beginning to provide data interoperability so that clients with more than one type of sensor or data-logger can use the software with which they have been provided.

To achieve improved fertiliser use efficiency through the use of remote sensing on a global scale, automated data retrieval and processing need to be provided. It is likely that these services will be offered to aid food production as part of aid packages to nations who have neither the means nor the skills to provide them. Providing information systems is easy in comparison to providing remote sensing processing capability as radio programmes and cellular telephone applications should be sufficient to provide a useful service.

Currently, remote sensing of agricultural crops by proximal sensors, as well as by aircraft and satellite is occurring. Farmers are using this information to monitor crop health and the farm environment. In the foreseeable future, farm information systems will be enhanced by hyperspectral remote sensed data, supplying whole farm spatial mineral maps of plant nutrient status. These data can then be used to provide variable-rate fertiliser

application maps which, when applied, will provide the correct nutrient required for optimal economic yield. A further benefit will be a reduction in runoff and atmospheric losses from the farm system to the environment, improving water quality and reducing greenhouse gas emissions.

Acknowledgments The authors would like to acknowledge the work of Dr. Reddy Pullinagari and Dr. Gabor Kereszturi in their work in correlating hyperspectral data to plant tissue wet chemistry. This paper was part of a workshop sponsored by the OECD Co-operative Research Programme on Biological Resource Management for Sustainable Agricultural Systems.

References

- Anon (2014). Crop nutrient contents – yield unit changes. Access Database from United States Department of Agriculture. Downloaded from: <http://www.plants.usda.gov/npk/Nutrientreport>. Accessed 30 July 2014.
- Anon. Ministry of Agriculture and Forestry (2010). Pastoral Sector Overview, downloaded from www.MAF.govt.nz Accessed 17 July 2010.
- Bretherton, M.R. (2012). An Investigation into Repellency – Induced Runoff and its Consequences in a New Zealand Hill Country Pasture System. Unpublished Thesis, Massey University Palmerston North, New Zealand.
- Cooke, G.W. (1982). *Fertilizing for maximum yield*. – 3rd (Ed). Granada Publishing Limited – technical Books Division (pp. 278–308) St Albans, Herts AL2 2NF.
- Fageria, N.D., Virupax, C.B., Jones, C.A. (2011). *Growth and Mineral Nutrition of Field Crops*. – 3rd (Ed). CRC Press Taylor and Francis Group.(pp. 219–517) Boca Raton, FL.
- Grafton, M. C. E., Yule, I. J., & Manning, M. J. (2013). A review of the economic impact of high levels of variance in fertiliser spreading systems. *Proceedings of the New Zealand Grassland Association*, 75, 131–136.
- Haag, L., (2014). PA lessons learned, dreams dreamt, and plans made: some perspectives of a U.S. High Plains Dryland Researcher and Farmer. In *Proceedings of the 17th Precision Agriculture Symposium of Australasia*. 68–75.
- Heffer, P., (2013). Assessment of Fertilizer Use by Crop at the Global Level. International Fertilizer Association. Downloaded from: www.fertilizer.org Accessed 7 August 2014.
- Holland K.H., Lamb D.W., Schepers J.S., (2012). Radiometry of Proximal Active Optical Sensors (AOS) for Agricultural Sensing. Selected Topics in Applied Earth Observations and Remote Sensing, *IEEE Journal of PP*:1–10. DOI: 10.1109/jstars.2012.2198049.
- Jarvis, P. J., Boswell, C. C., Metherell, A. K., Davison, R. M., & Murphy, J. A. (2002). A nutrient budget for the Meat and Wool Economic Service of a New Zealand Class 1 high – country farm model. *New Zealand Journal of Agricultural Research*, 45, 1–15.
- Kuri, F., Murwira, A., Murwira, K., & Masocha, M. (2014). Predicting maize yield in Zimbabwe using dry dekads derived from remotely sensed vegetation condition index. *International Journal of Applied Earth Observation and Geoinformation*, 33, 39–46.
- Mackenzie, C., (2013). Utilising Variable Rate Fertiliser Application to improve Farm Profit. In: *Accurate and efficient use of nutrients on farms*. (Eds. L.D. Currie and C.L. Christensen). <http://frc.massey>.

- ac.nz/publications.html. Occasional Report No. 26. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pages 1.
- Mersmann, M., Walthers, S., and Sia, T., (2013). Fertilizer Application – Driving the Future with Innovations. In: *Accurate and efficient use of nutrients on farms*. (Eds. L.D. Currie and C.L. Christensen). <http://flrc.massey.ac.nz/publications.html>. Occasional Report No. 26. Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pages 13.
- Pullanagari, R., Yule, I., Tuohy, M., Hedley, M., Dynes, R., & King, W. (2012). In-field hyperspectral proximal sensing for estimating quality parameters of mixed pasture. *Precision Agriculture*, 13(3), 351–369.
- Pullanagari, R. R., Yule, I. J., Tuohy, M. P., Hedley, M. J., Dynes, R. A., & King, W. M. (2013). Proximal sensing of the seasonal variability of pasture nutritive value using multispectral radiometry. *Grass and Forage Science*, 68(1), 110–119.
- Rahmann, M. M., Lamb, D. W., Stanley, J. N., & Trotter, M. G. (2014). Use of proximal sensors to evaluate at the sub-paddock scale a pasture growth-rate model based on light-use efficiency. *Crop and Pasture Science*, 65, 400–409.
- Scott, D., Robertson, J. S., & Hoglund, J. H. (2006). Considerations in low fertiliser rate application in the high country. *New Zealand Journal of Agricultural Research*, 49, 59–65.
- Solari, F., Shanahan, J., Ferguson, R., Schepers, J., & Gitelson, A. (2008). Active sensor reflectance measurements of corn nitrogen status and yield potential. *Agronomy Journal*, 100, 571.
- Starks, P. J., Zhao, D., & Brown, M. A. (2008). Estimation of nitrogen concentration and in vitro dry matter digestibility of herbage of warm-season grass pastures from canopy hyperspectral reflectance measurements. *Grass and Forage Science*, 63, 168–178.
- Torino, M. S., Ortiz, B. V., Fulton, J. P., Balkcom, K. S., & Wood, C. W. (2014). Evaluation of vegetation indices for early assessment of corn status and yield potential in the South Eastern United States. *Agronomy Journal*, 106(4), 1389–1401.
- Wan, L., Zhang, B., Kemp, P., & Xianglin, L. (2009). Modelling the abundance of three key plant species in New Zealand hill-pasture using a decision tree approach. *Ecological Modelling*, 220, 1819–1825.
- Xingha, L., Huanfeng, S., Liangpei, Z., Hongyan, Z., Quiandquiang, Y., & Gang, Y. (2014). Recovering qualitative remote sensing products contaminated by thick clouds and shadows using multispectral dictionary learning. *IEEE Transactions of Geoscience and Remote Sensing*, 52(11), 7086–7096.
- Yule, I.J., and Grafton, M.C.E., (2010). Factors Affecting Fertiliser Application Uniformity. In: *Farming's Future minimising Footprints and maximising Margins*. (Eds. L.D.

Currie and C.L. Christensen). <http://flrc.massey.ac.nz/publications.html>. Occasional Report No. 23. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 413–420.



Miles Grafton worked as a Management Accountant and GIS technician in the agricultural aviation industry for a number of years. His Ph.D. research was in identifying causes of material flow problems in aircraft. He has also been involved in developing computer controlled automated delivery systems for variable rate application of bulk solids from agricultural aircraft.

He spent 3 years working as a research scientist for a major fertiliser manufacturer in applica-

tion science and spreading quality improvement.

He works in Precision Agriculture (PA) and has been involved in modelling fertiliser ballistics for improved application accuracy and quantifying the benefits of PA.



Ian Yule is Professor in Precision Agriculture at Massey University in Palmerston North where he has been working for 17 years. He is an engineer by training and education and holds a Ph.D. from the University of Newcastle upon Tyne in England where he worked previously. Professor Yule has tended to work in applied areas such as pasture measurement and soil mapping which have the potential to benefit farmers. Through his work in pasture measurement and precision agriculture he has

developed a strong interest in remote sensing and understanding how it can be harnessed to improve farm performance and nutrient use efficiency.