Will site specific nutrient management live up to expectation?

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Abstract

Sustainable farming systems require soil fertility status to be maintained at a level that supports satisfactory plant growth while minimising nutrient loss to the environment. Because soils within farmed landscapes are heterogeneous, the amount of nutrients required to support optimal plant growth will differ in relation to soil type, the soil's nutrient status, the crop's growth potential within the various landscape zones, and time of nutrient application in relation to plant growth stage. Fertiliser application rates could also possibly be determined politically by environmental regulation. Site Specific Nutrient Management (SSNM) is a major component of Precision Agriculture and relates to the differential management of soil nutrients between landscape zones. Specialist advisers in SSNM may be needed to interpret crop yield data in relation to status of the farm's other resources and to help farmers formulate their farm's fertiliser plan. Cost of describing resource status and lack of specialist consultants are identified as significant impediments to uptake of SSNM technologies. SSNM is likely to be widely implemented only where subsidies are paid or where regulations and quality assurance schemes demand environmental standards are met. Examples are presented of successful use of SSNM on intensive cropping farms and low-input grazed pastures. Suggestions are offered as to how SSNM technologies must evolve to deliver their potential for improved productive, economic, environmental and social outcomes in advanced and developing countries.

Keywords: decision support, soil fertility, fertilisation, spatial variability, precision agriculture, remote sensing, sustainability, economics; social, environment

Zusammenfassung

Kann variable Düngung den Erwartungen gerecht werden?

Nachhaltige Landbewirtschaftungssysteme erhalten die Bodenfruchtbarkeit auf einem Niveau, welches das Pflanzenwachstum in ausreichendem Maß fördert und Nährstoffverluste in die Umwelt minimiert. Da landwirtschaftliche Böden heterogen sind, das Ertragspotential und die Ansprüche an die Nährstoffversorgung standortabhängig variieren, ändert sich auch der Düngebedarf an Nährstoffen entsprechend. Theoretisch möglich wäre eine Regulierung der Aufwandmengen auf politischer Ebene. Die variable Ausbringung von Düngemitteln ist Bestandteil des Precision Agriculture und reguliert die Ausbringungsmenge auf Grundlage der Variabilität von Standortmerkmalen. Die Verifizierung kausaler Zusammenhänge zwischen Ertragsdaten und standorttypischen Eigenschaften und betriebsspezifischen Merkmalen setzt in diesem Zusammenhang ein entsprechendes Fachwissen voraus, um räumlich variable Karten für die Düngung zu erstellen. Mittlerweile hat sich gezeigt, dass insbesondere fehlende geokodierte Standortinformationen und ein Mangel an Experten für deren Interpretation, die Implementierung dieser Technologie auf den Betrieben verhindert. Auch sind positive Beispiele für die Rentabilität dieser Technologie eher selten, so dass deren Implementierung derzeit nur durch Subventionen, oder zur Einhaltung von Umweltstandards gefördert werden könnte. Im vorliegenden Beitrag werden Beispiele für einen erfolgreichen Einsatz variabler Düngung in intensiven viehlosen landwirtschaftlichen Betrieben und extensiven Grünlandbetrieben aufgezeigt. Es werden Vorschläge für eine zukünftige Entwicklung der variablen Düngung aufgezeigt, die agronomischen, ökonomischen, ökologischen und sozialen Ansprüchen in Industrie- und Entwicklungsländern gerecht werden.

Schlüsselworte: Bodenfruchtbarkeit, Düngung, räumliche Variabilität, Precision Agriculture, Fernerkundung, Nachhaltigkeit, Ökonomie, Soziales, Umwelt

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Introduction

Soil is a living organism that changes in space and in time, thereby affecting availability of plant available nutrients. The spatial variation in soil type, even within one-to-two-ha paddocks, offers farmers scope to differentially manage nutrient applications to these contrasting areas of the farm. The term land management units (LMUs) is used in this paper to describe a unit of land that expresses a reasonably uniform combination of yield-influencing factors, consistently across years, for which a single combination of nutrient inputs (Florin et al., 2005) and management may be suitable to optimise the response of the crop or pasture. Yield sensors and GPS are standard items on farm machinery in many developed countries heavily involved in crop production, with the result that these farmers may now have yield maps from cropped areas of their farm for up to 20 years. Site Specific Nutrient Management (SSNM) is the application of nutrients to meet the specific needs of plants within the pre-defined, spatially explicit LMUs, by way of variable rate fertiliser application technologies (Haneklaus and Schnug, 2006).

Early developers of SSNM aimed at correcting soil nutrient deficiencies so that field crop production would become uniform. Nowadays, when discussing pros and cons of precision agriculture (PA) technologies, the potential loss of biodiversity needs to be considered in the advent of implementation of the technology. Because the soil nutrient that is supplied is not always the growth limiting resource, this approach is flawed. Common limitations to yield are soil texture and structure, which reflect the soil's water holding capacity and aeration state. The preferred approach to SSNM is rather to optimise the crop's growth potential within each LMU, such that the better growing soils receive more fertiliser, and the poorer growth zones less fertiliser than the average used in conventional fertiliser strategies. Indeed, some poor growing areas are now often not planted, since the cost of production in these areas can exceed the value of the crop grown.

SSNM promotes agricultural sustainability through improved nutrient efficiency, higher net financial returns, protection of natural resources and minimisation of nutrient emissions to the environment. Efficiency gains also arise through the ability of these technologies to ensure the land is covered exactly with specific rates of seed, fertiliser and pesticides, and with no overlap of, or gaps between, adjacent rows (Fowler 2005).

Since these technologies have been available for up to 20 years, one might have expected to see them widely used in agriculture – particularly in cropping systems. This is not the case, so we ask "why not?"

This review also looks at PA opportunities in grazed pastures, where farmer involvement partially substitutes the high-cost, high-technology processes synonymous with SSNM for cropping.

Identifying soil variability

Perhaps the most difficult and costly task within SSNM is to identify the location and cause of variable crop or pasture yield. While grain harvesters can routinely generate within-paddock yield maps that depict yield variation, it is often far from clear why this variation occurs. In grasslands, identifying spatial and temporal variation in pasture production across a farm is very difficult, though manageable (Paulsen and Schnug, 2003).

Under the right conditions aerial photography of ploughed fields can provide a clear delineation of soil type variation that can be digitised into a GIS layer and characterised by pedological survey. Such classification is generally impossible with permanent pastures as the soil surface is obscured by vegetation. Electrical conductivity (EC) survey mapping is becoming more widely used to assist in identifying soil differences on farms (e.g. Florin et al., 2005; McBratney et al., 2005). The soil maps are generated by ground-truthing zones of differing EC values against pedological description of soil profiles. While this has proven successful in many situations, especially for determination of clay content, factors other than clay content can affect the EC reading (Lund et al., 2005; McBratney et al., 2005). EC maps of four sites on a New Zealand, free-draining pumice soil bore no resemblance to the soil map generated by visual pedological description (W. Rijkse, unpublished data). Whereas soil test data are widely used to help establish LMUs, Florin et al. (2005) highlight the sometimes prohibitive cost of obtaining spatially-dense soil-test data as a disincentive to use this method of soil classification.

Defining LMUs

Spatial statistics (GeoStatistics) enable the determination of spatial variability of a variable within and between paddocks. Where spatial variability exists, one can set acceptable limits (SD and CV) to determine minimum sampling distance from which to take soil samples. In one experiment, where only the average of the *Illinois Soil Nitrogen Test* variable (with a small standard deviation) was required for each of the 14 paddocks, Ruffo et al. (2005) determined that only 10 samples per paddock were needed to give an accuracy of 24 mg N kg^{-1}. With the semi-variogram 'range' across all of these paddocks being 150 m, the 10 samples needed to be < 150 m apart.

Where only a few data are available to adequately map a variable within a paddock by traditional soil sampling (e.g. clay content), the *maximum likelihood variogram* enables

better mapping prediction than the *moments variogram* (Kerry and Oliver, 2005a). Their recommended approach is 1) determining the appropriate sampling interval using a variogram from ancillary sites, 2) sample the field at just less than half the variogram's range, and 3) choose additional sites at half that range, to give a total 50 - 60 sites. This approach is much more efficient than sampling the 100 - 150 soil cores needed if using the variogram based on the Monte Carlo sampling approach. Soil sampling within a grid structure is superior to random sampling due to the ability to utilise spatial correlations to increase the predictive power of the analysis (Peck and Melsted, 1967; Sabbe and Marx, 1987).

Soil sampling costs can also be reduced by co-kriging. This method predicts the values of more expensive soil tests from the higher sampling density of cheaper and/or more easily obtained soil parameters (e.g. moisture correction factor), that are highly correlated to expensive/time consuming tests (e.g. volumetric water content) (Kerry and Oliver, 2005b). In grazed pastures the distance between sampling sites needs to be closer than in cropped soils because of the influence of random animal excreta depositions and absence of homogenizing soil tillage operations (Shi et al., 2000).

Typically, in Australasia, detailed soil sampling may be done in only 2 to 3 paddocks on a farm, whereas management decisions will affect the whole farm, with much less detailed data. Directed (targeted or smart) sampling of zones already defined by existing spatial information can reduce costs considerably, compared to grid sampling (McBratney and Whelan, 1999; Mulla, 1997; Schnug and Haneklaus, 1998), with such zones being defined by remote sensing or crop yield data, and the use of fuzzy partitioning (Lark, 2001; Shatar and McBratney, 1999). Further reduction in sampling effort can be achieved where LMUs have consistently yielded to their potential over a period of time and where the LMUs cover the complete range of variation in soil properties and their temporal fluctuations (Larscheid et al., 1997). With efficient sampling and subsequent modelling the overall cost of defining a farm's LMUs can be reduced (Florin et al., 2005).

Temporal variability of some soil nutrients and soil physical characteristics will dictate which method and sampling frequency to use when determining nutrient status and resource condition. Highly soluble nitrogen (N) and sulphur (S), which can fluctuate almost daily, can be regularly sampled by: standard soil test or on-board sensors; dynamic modelling of crop growth; remote sensing; or by inference from site characteristics such as slope, which affects runoff, drainage and erosion losses (Bloem, 1998; Haneklaus et al., 1999). Less mobile phosphorus (P) and potassium (K) need be tested only every 3 - 5 years and pH every 5 - 10 years. Each geo-referenced soil sample should comprise a bulking of several samples from within no more than a 10 m^2 zones about the selected position (Hergert, 1997). However, until spatial and temporal variability within the paddock is known, there is no point in considering SSNM to improve crop yield (Castrignano et al., 2005).

Satellite and land based remote sensors to aid nutrient planning

Satellite multi-spectral imaging is becoming more widely used in agricultural feed and nutrient planning applications and may also enable detection of crop nutrient status. For example, the Australian *Pastures From Space* (Gherardi et al., 2005), and the European *Farmstar* decision support tool for crop management (Coquil and Bordes, 2005) are two approaches now being used. To be useful for feed budgeting and to a less extent nutrient budgeting, Moran (2000) states that practitioners require: rapid delivery of geo-referenced data to an accuracy of 1 pixel; 70 - 75 % accuracy of information about soil or crop conditions; repeat land coverage frequency from between twice per week to bi-weekly; spatial resolution of 10 - 20 m; maps with quantitative data; and all at a fair price. In many environments cloud cover at critical stages of crop development will prevent image capture at the necessary frequency or critical times, especially with Landsat-TM that has a 16-day return rate. Even when using lower resolution, daily MODIS imaging, landscapes in many countries will still not be imaged on a regular basis due to cloud cover and will thus not greatly assist farmers in determining nutrient sufficiency. High resolution imaging does enable determination of crop growth rate and, thereby, the possible need for additional fertiliser, but satellite remote sensing to determine nutrient status of ploughed fields appears unlikely (Panten, 2002). This is due in part to the N status of plants reflecting not only available soil N status or protein content, but also soil moisture content, soil fertility, plant disease and disorders (Haneklaus and Schnug, 2006). Thus, to determine the cause of N variation in a field crop, ground truth campaigns which can be expensive and time demanding .

Land-based sensors such as LASSIE (Schnug et al., 2000) that provide real-time images of crop or pasture growth, independent of weather conditions, enables early detection of differential growth. Following directed ground truth sampling, a quick response by variable rate nutrient or pesticide application can be made. Sensors on fertiliser spreading machinery are now being used for differential application of N. Forward scanning sensors (e.g. *Yara N-sensor* and *GreenSeeker*) that use differential crop reflectance to determine N status of the crop (Bredemeier and Schmidhalter, 2005) enable adjustment of the N application rate on-the-go. However, this technology assumes

that the reflected signature of the crop is affected only by available soil N, but, as with satellite imaging, colour variation may be due also to deficiency of other nutrients, soil moisture, row spacing, soil colour, time of day and cloudiness, as well as canopy architecture, measuring angle, solar zenith and crop variety (Bredemeier and Schmidhalter, 2005). On-the-go sensors for other plant nutrients and soil characteristics are being developed (Sudholter at al., 2005; Lund et al., 2005).

SSNM of grazed pastures

As most fertiliser is applied to grazed pastures by broadcast application, the minimum size of the manageable LMU will be much greater than the areas where fertiliser is drilled or injected directly into the soil. The smallest LMU for broadcast fertiliser is determined mainly by spread-width of the fertiliser spreader and the time taken to change the fertiliser rate on-the-go.

Betteridge et al. (2002) measured pasture mass and soil fertility at 120 sites within a 2 ha, flat, dairy pasture and, using principle components analyses, created 3 LMUs, amongst which herbage mass ranged from 1900 to 2670 kg dry matter (DM) growth ha^{-1} over winter. N-fertiliser response trials in each of these LMUs revealed a site by season interaction in growth responses, which reflected soil texture differences at this small scale. They found that if the N fertiliser used on LMU 3 was applied to LMU 1, overall pasture growth would have increased 7 %, but by withholding fertiliser N from LMU 2, there would have been a 33 % cost saving over the spring and early summer measurement periods. Interestingly, land contour and local knowledge of drainage characteristics could have defined these three LMUs without using the high cost of intensive soil sampling and EC mapping. The significance of the local knowledge for SSNM is comprehensively discussed by Haneklaus and Schnug (2006).

New Zealand hill country farms are characteristically variable in topography, soils and associated pasture productivity. They are grazed as a mixed-livestock enterprise comprising sheep, cattle and sometimes deer. In hill country, livestock transfer fertility from slopes to camp sites on ridges or valley floors (Gillingham and During, 1973; Gillingham et al., 1980); erosion removes soil and particulate-bound P (Gillingham and Thorrold, 2000) and leachate transfers soluble nutrients from upslope regions to groundwater and seepage sites further down slope (Bloem, 1998). Such factors contribute to spatial variation in pasture mass.

When measuring spatial variability of pasture DM in a rotational grazing regime, on any one measurement day, the duration of pasture regrowth 'since last grazing' is different amongst the paddocks. This spatial variation will easily exceed landscape-inherent spatial variation. With animals set-stocked across the farm, farmers intuitively stock paddocks so that animal numbers match feed supply. Thus, spatial variation in pasture growth potential is represented by stock density rather than pasture DM. In both grazing regimes, pasture exclusion cages are needed to adequately determine variation in growth across a farm – a task that is only practical in a research context. A practical approach to determining LMUs for grazed pastures has been developed in New Zealand. Farmers are taught how to describe soil profiles (colour, texture and structure). This knowledge is used, in conjunction with land contour and local knowledge of how the soils respond to management, to map their farm's LMUs (Mackay et al., 2001). The LMU boundaries, drawn onto the farm's aerial photograph, are then digitised for calculation of LMU areas within a GIS framework. Management decisions are devised that recognise the *opportunities* and *constraints* to management of each LMU, and the plans are then implemented. Using this approach, farmers have sometimes identified new, more profitable land uses that improve the farm's capital resource efficiency (land, fertiliser, drainage) and increases profit.

Precise fertiliser placement

Spatial matching of GIS data layers is crucial for SSNM to provide the required gains in economic and environmental efficiency. This requires the ortho-correction of the farm's aerial photograph over which other input data sets are placed, using the same geo-reference system. Other aspects of quality control that must also be considered include: calibration of the fertiliser spreader to the required specification of variance; knowledge of the crop's fertiliser response at the various times of the year; use of soil and contour maps that are valid at the within-paddock scale; and avoidance of fertiliser placement near waterways, roads and buildings.

Fertiliser prescription maps depend upon correct parameterisation of the growth model that determines nutrient requirements of the crop. From these models, nutrient prescriptions are determined by specialists who understand soil chemical processes. While SSNM practitioners and consultants must assume these models are correct, they have the responsibility of ensuring that the model is applicable to the farm's situation to which it is being extrapolated.

New Zealand examples

On many New Zealand ground-spread fertiliser spreaders, application rate cannot be automatically altered on-the-go and so the paddock often becomes the smallest

LMU that can be differentially fertilised. While modern ground spread vehicles could be fitted with variable rate capability, most farmers are unwilling to pay the additional cost for use of these vehicles and consequently, New Zealand fertiliser spreading companies are reluctant to invest in this technology (L. Pederson, pers comm.).

For SSNM prescription mapping, farm maps of geology, pedology and geomorphology should be 1:5000 or better (Haneklaus and Schnug, 2006), yet in New Zealand the most readily available public soil and contour maps are at best a 1:20 000 scale and often 1:50 000. Working at the within-farm scale requires digital elevation maps and appropriate scaled soil maps to ensure the benefits of SSNM are achieved. Low resolution contour maps can introduce large errors in estimated slope class areas and the horizontal placement of soil groups, relative to contour (Costall et al., 2001).

In grazed hill country, fertiliser is normally applied at only one rate, by fixed-wing aircraft or helicopter. While P fertilisers promote legume growth and, therefore, nitrogen N fixation in the warmer months, use of N fertiliser is increasing. Single-rate fertiliser application ignores the high variation in soil fertility known to exist on such farms and misses the opportunity that exists to optimise the use of these nutrients. Using only land contour to create LMUs, a very simple approach to SSNM is to apply N fertiliser on north and west steeper slopes in autumn (April – June) when soil warmth and moisture is adequate for grass growth. In contrast, P fertiliser can be applied at any time of year to south and east slopes which have a higher legume content and where the summer is cool and moist, allowing for clover fixation of atmospheric N. North and west facing slopes are too dry for active clover growth and N fixation in summer and early autumn. In New Zealand hill country SSNM can thus be managed on a very simple basis - different types of fertiliser at appropriate times of the year, on different land aspects. Thus, hill pastures present a great potential for variable rate fertiliser application, not only through different fertiliser types for north and south facing aspects, but also for differential rates on the low, moderate, and steep slopes, with no fertiliser applied on or near to streams. The modelled relative response to differential fertiliser was estimated to be about 10 % and 7.5 % net margin from a high and a low fertility site, respectively, compared to uniform fertiliser application (Gillingham et al., 1999; Gillingham et al., 2003).

Aerial topdressing aircraft applied 392,000 tonne of fertiliser to New Zealand farms between June 2003 and March 2004 (Murray and Yule, 2005) with many using GPS tracking. Recently, a New Zealand fixed-wing aircraft has been modified to apply on-the-go differential rates of fertiliser to the landscape. Using a precision GIS fertiliser map this plane can fly at 120 knots over hill farms with broken and variable contour, tracks and streams, delivering fertiliser at rates appropriate to the LMUs below.

SSNM in developing countries

Short term prospects for implementing sophisticated SSNM strategies generally do not look bright. Not only are the farms small, or perhaps even based on nomadic methods where land ownership is ambiguous. If land is owned at all, the volume of commodities for sale are so small and the prices received are generally so low, that investment in even basic inputs such as fertiliser, may not be an option. Often tropical agricultural systems 'mine' plant nutrients rather than apply excessive rates of fertiliser (Stoorvogel and Bouma, 2005). Furthermore, farmers in these environments are generally price takers who react to signals set by importers. For example: tariffs may limit imports; food safety regulations determine pesticide limits; and developed countries may demand imports come only from sustainably managed systems and, increasingly, from countries using Track & Trace systems. Thus producers of tropical crops for export, are likely to be large organisations that can manage production within these exacting external constraints. Most producers of tropical crops own very small land units. Nevertheless, several examples of the successful application of SSNM practices on small Thai holdings are presented in the Proceedings of the XIVth World Fertilizer Congress in Chiang Mai, Thailand (Eichler-Loebermann et al., 2008).

Hannaway et al. (2005) highlighted 'the digital divide' that challenges developing nations. Their needs include the full spectrum of computing hardware, software, computing infrastructure and skilled operators. Even if these needs are not limiting, the high cost of proprietary vs. 'open source' software and associated high licence fees severely limits the probable adoption of SSNM. "Development of integrated solutions is often impeded by the cost of data or the regulations preventing the sharing or sale of base layer information" (Hannaway et al., 2005). Notwithstanding these impediments farmers can and do employ simple, low-cost SSNM systems on small farms where appropriate education and extension services are available. Thailand's Royal Development Programmes described in these Proceedings provide good examples of successful extension work (Attanandana et al., 2008; Boonsompopphan et al., 2008; Soitong and Vearasilp, 2008).

In Thailand a large number of farms are less than 1.0 ha in size and in Chiang Mai province they average only about 0.4 ha. Thus, SSNM technologies are not used; farmers rely on past experience, trial and error, and on fertiliser recommendations from the extension officials (M. Ekasingh pers comm.). Examples of PA and SSNM for paddy rice, tea and palm plantations are described by Brown (2002).

However, Stoorvogel and Bouma (2005) showed how Costa Rican banana producers formed a collective that enabled PA technologies, with SSNM, to be employed. For a large plantation, systems were developed to map banana yields which were then linked to the soils map. Using a variable rate fertilisation approach, the 111 ha Rebusca plantation made a 12 % fertiliser saving from its 2400 kg ha^{-1} yr^{-1} fertiliser usage. The success of PA on this plantation involved integrated inclusion of all aspects of plantation management and intensive involvement of the plantation manager in the development and implementation of the PA strategy.

While formation of co-operatives is one way in which SSNM principles can be implemented, external forces may be required to make this happen.

As crop growth models are not available for many tropical crops (including bananas), fertiliser response trials will be needed to determine nutrient needs of the range of soils to enable SSNM.

Sources of error in SSNM

Fertiliser application

On cropping farms, fertiliser and lime may be broadcast before sowing and/or accurately placed under or beside the seed at sowing. During crop growth, fertilisers will probably be broadcast using either ground or aerial applicators. In areas with confinement livestock systems, slurry may also be spread over or injected into the soil prior to sowing.

Data on precision placement of fertiliser drilled at seeding time are scarce but Moller and Svennson (1991) quote coefficients of variation of 5 and 9 % for a full-width pneumatic spreader. The precision of fertiliser placement by Cross Slot® direct drilling is less than 10 % within a 20 mm wide band, adjacent to but separated from the sown seed, and repeated across the machine in 150 mm row spacing (J. Baker, pers comm.). This careful fertiliser placement is believed to minimise leaching prior to full root establishment.

Variation in nutrient application rate by broadcast sowing is higher than when applied by seed drill. For example, in New Zealand, where fertiliser trucks are "certified" N fertiliser (urea pellets) placement has a coefficient of variation (CV) of 15 % or less, and superphosphate (P, S, Ca) compound fertilisers a CV of 25 % about the intended application rate. Actual application rates vary for several reasons. Lawrence et al., (2005) showed that twin-disc spreaders on fertiliser trucks have inherent errors in spread pattern that contribute to error in variable rate application, especially when a 50 % intentional overlap is factored in to the spreading pattern to achieve the given application rate. Field size and shape significantly impact accuracy of variable rate fertiliser distribution with twin disc spreaders. The accuracy increases as, to be more economically efficient, spreading machines are made bigger to provide a wider spread (Lawrence et al., 2005). Ground-spread variation from certified trucks can be over 50 % of the intended rate due to unplanned overlap resulting from complex paddock shape (Yule et al., 2005; L. Pederson, pers comm.) and longitudinal spread variation due to uneven flow of fertiliser to the spinning discs (Yule et al., 2005). Also, variable moisture content, granule size and bulk density of each batch of fertiliser, affects the spread width. Therefore, each batch of fertiliser needs to be tested to ensure correct calibration of the spreader. In practice, however, this is often not done.

GPS logging of fertiliser vehicles and fertiliser application is becoming more widely used to provide evidence to the farmer or environmental auditor of what fertiliser was applied, when, and where. On-the-go logging helps the driver to minimises overlap (L. Pederson pers comm.).

Uniform rate aerial application of phosphatic fertiliser by fixed-wing planes ranged from 37 - 67 % (CV) and by helicopter by 12 - 20 % (Gillingham, 1981). Errors are attributed to uneven lateral distribution due to uneven flight path tracking and variable flow though the hopper (Gillingham and Metherell, 2005).

Uneven broadcast-spread of phosphatic fertiliser has minimal effect on pasture production or soil Olsen P test as variation in spatial distribution between years smoothes out present-year variation, and because most surplus P is retained in the rooting zone for later plant uptake. Similarly, poor distribution of N applied to pastures will have minimal, if any, effect on paddock productivity since most application rates are within the zone of linear response (Gillingham and Metherell, 2005).

Another error that will occasionally arise, with any method of fertiliser application, is the use of the wrong fertiliser. This could be because of errors in: calculated nutrient requirement; placement of the original order; fertiliser mixing at the bulk store; or the loading of the wrong fertiliser mix at the bulk store or on the farm (L. Pederson, pers comm.).

Nutrient Response Curves

To deliver optimum (+/- 10 %) agronomic or economic production through SSNM, an appropriate fertiliser response model is needed. These models may be well established for crops in some areas of the world, but not in others. Thus, errors due to extrapolation beyond the bounds of modelled data will undoubtedly arise.

For grazed pastures, response models are commonly developed in small-plot trials, cut with a mower. If clippings

are returned, then they are generally evenly spread over the plot. But, in grazed pastures, recycled nutrients are randomly distributed in faeces and urine, with the concentration in urine being highly variable (Betteridge et al., 2005b). Interestingly, Morton and Roberts (2001) reported that relative P response curves were similar, whether measured under grazing exclusion cages in dairy pasture or by mowing, although the absolute response over the 4-year trial period differed.

Errors may also arise because trial designs typically minimise spatial variability by blocking areas of similarity in soil and/or contour features, such that response curves provide an 'average' optimum response for that soil and location. 'Average' optimum levels are contrary to the thesis of SSNM where optimum performance from a field will be achieved by applying nutrients to each LMU within and between paddocks at their optimum rates (Haneklaus and Schnug, 2006).

Finally, it is often assumed that each nutrient has just one optimum level, regardless of the availability of all other nutrients and soil water. While trial designs may have all 'other nutrients' non-limiting, this will rarely apply in practice. In fact the optimum level of 'other nutrients' may well be unknown. As non-limiting soil moisture conditions might only apply to research trials, this condition is unlikely to be found in most environments (e.g. Australia, Whelan and Taylor 2005), hence response functions will frequently not translate to commercial farms.

With the large range of possible errors arising from all phases of farm nutrient planning and implementation, high quality standards and control measures must be devised and implemented to maximise the chance of receiving the theoretical benefits of SSNM (Haneklaus and Schnug, 2006).

Smit et al. (2000) believe that it is preferable to look for response differences of the crop to management in each of the LMUs rather than to focus on components of soil fertility in the different LMUs that might drive the crop responses.

Auto-steer

Real-Time-Kinematic (RTK)-GPS, using dual frequency receivers, enables farm machines to track at 25 mm accuracy (Berglund and Buick, 2005). This system is widely used in conjunction with tractor auto-steer systems. But for many producers auto-steer is still used "as a new toy for the boy" (D. Varner pers comm.). On a positive note farmers see the advent of RTK-GPS and auto-guidance allowing tractor operators to switch their attention from driving, to ensuring fertiliser, seed and pesticide sowing activities perform to expectation (Fowler, 2005). "At present farmers are unlikely to leave the planting rig to sow the crop, unattended, as there is so much that might go wrong, not only to the quarter million dollar machines, but also to the final crop yield" (C. Fowler, pers comm.). Collectively, an advantage claimed for auto-steer is a reduction in driver fatigue that allows more time to be spent in the field each day.

In Nebraska, on rolling land in units of 53 ha, it is almost impossible to site the base station in one position to cover the whole field. Thus the inconvenience of shifting the base station to ensure line-of-sight to the tractor's receiver, is perceived as an impediment to adoption. Also, "While auto-steer may produce gains of US$ 5/acre (less overlap, 24-hour operations and night time spraying). Because large machinery is used, the whole planting operation may take only one or two days, so how can you justify the US$ 10,000 - 20,000 expense of this technology?" (J. Crofoot, pers comm.). Furthermore, quantification of the supposed benefits are scare or anecdotal (Whelan and Taylor, 2005). When significant time saving is assured, then high cost SSNM tools (variable rate fertiliser placement and auto-steer) may be appropriate.

Auto-steer enables precise year-to-year placement of agricultural inputs in the soil. To minimise the impact of soil compaction on crop growth, auto-steer ensures farm vehicles follow exactly in the same wheel tracks each year. This is now creating a new problem namely, with no-till planting, where and how should soils be best sampled, as fertiliser bands are always within the same narrow sowing strips?

Altering pH to achieve SSNM

In developing countries where economics of production limits use of chemical fertilisers; in organic farming systems that restrict the types of nutrients that can be used; and in any country where environmental limitations restrict fertiliser inputs, SSNM strategies can be used to increase the availability of existing soil minerals through altering their solubility (Haneklaus and Schnug, 2006). This can be achieved by changing soil acidity with relatively cheap lime or elemental sulphur. As soil pH is one of the most important factors influencing the mobility of soil nutrients (Schnug and Fink, 1982), manipulation of pH can, for example, be used to reduce the availability of toxic heavy metals such as cadmium (Bruemmer et al., 1986).

Agricultural waste products and SSNM

A common problem on many farms that receive nutrients from slurry or other organic waste products is that of heterogeneity of nutrients and dry matter content of the various waste products used. Standard nutrient values may be adequate in some circumstances, but where qual-

ity assurance (QA) is required to ensure nutrient optimisation for plant growth, or that environmental regulations are being met, strategies such as thorough mixing of these batches or frequent analyses of the product (even on-the-go) may be necessary. Organic animal wastes tend to have a fixed N:P:K ratio that adds to the complexity of balancing nutrients to meet optimum plant needs (Haneklaus and Schnug, 2006).

In New Zealand, there are currently no constraints on fertiliser inputs, yet most dairy farmers are required to apply dairy-shed effluent (DSE) to pasture (10 - 20 % of the farmed area) to reduce stream pollution. Many of these farmers still apply the same rate of fertiliser to the pastures receiving DSE as they do to the rest of the farm. In one survey of 2 paddocks on each of the 10 farms, the soil Olsen P test was > 100 mg P l^{-1} in 2 DSE paddocks. However, agronomic responses are rarely found at Olsen P > 40 mg P l^{-1} of the top producing 25 % of dairy farms, or > 30 mg P l^{-1} for the remaining 75 % of farms (Betteridge et al., 2005). Average Olsen P of all 20 paddocks, was 63 mg P l^{-1}. In that situation, which is believed to be representative of hundreds of dairy farms in the region, SSNM requires no greater input than to stop further fertiliser P inputs until the 'target' Olsen P value in each paddock is reached. Alternatively, low rates of P may be used to provide the 'carrier' for S and K nutrients. In this latter situation, variable rate P fertilisation would be well worth pursuing. In a study in Queensland, Australia, organic waste was being applied to pasture or crop land as a means of disposal. Because the waste was free, the A$ 7.70 ha^{-1} soil test cost was unjustified and so the application was at the farmers whim (M. Redding, pers comm.). Environmental restrictions might alter this practice instantly!

When more than one nutrient is required to optimise growth, careful planning over two or three years may be necessary to ensure that the correct compound fertilisers are applied at the correct rates, so that no one nutrient gets seriously out of balance with the others (Haneklaus and Schnug, 2006). This is likely to require a good fertiliser consultant and good record keeping by the farmer.

Environment

Environmental regulation is likely to be the single greatest pressure leading to farmer adoption of PA technologies. SSNM helps producers maintain nutrient applications within prescribed limits and, importantly, provides farmers the opportunity to log and map how much fertiliser was applied to each land unit and when. Some producers are reported to use PA maps to prove to environmental auditors that "The pollution event was not caused by me" (J. Bouma, pers comm.). A positive application of PA is to verify that fertiliser management is within environmental limits and, in increasingly more situations, that 'QA requirements of supply' are below the required limits.

In the Netherlands, only very efficient farms can now survive under current market conditions (Stoorvogel and Bouma, 2005), yet Dutch farmers using the MINAS plan (Mineral Accounting System) for soil nutrient management, have achieved a 30 % reduction in fertiliser inputs with no reduction in productivity. Although Dutch farms are close to their optimum production, Stoorvogel and Bouma (2005) believe further efficiency gains are possible from improved quality of agricultural products; improved efficiency of pest and disease control; and by managing the resource variability on farms. In their *case study*, four management zones were identified on an 81 ha cropping farm (winter wheat, potatoes and sugar beet), based on the soils functional potential for production and leaching risk. Using a crop simulation model and real-time weather data to predict weekly N requirements, 23 % less N fertiliser was used, compared to the standard recommendation of extension specialists. Nitrate leaching was also estimated to have been reduced by 55 kg nitrate-N ha^{-1} (Stoorvogel and Bouma, 2005). In Denmark, N losses through leaching were reduced by 48 % simply through a crop rotation based on balanced N fertilisation with due regard to organic N sources by farmyard manure (Thysen, 2005). Matching the N demand of the crop plants with variable rate N input might help to further improve the N use efficiency whilst optimising crop yield and quality as well as further reducing environmental burdens.

Economics

The most common factor relating to low adoption of PA has been the lack of clearly demonstrated economic benefits (Lowenberg-DeBoer and Boehlje, 1996; Haneklaus and Schnug, 2006). Because of the high costs of PA technologies, farmers require demonstration of clear cost benefits before they will adopt the technology, but current pricing and subsidy levels are insufficient to ensure PA is adopted by Dutch farmers (Smit et al., 2000). Other impediments to adoption of PA strategies include the lack of integrating technologies to link yield variation to real-time crop needs and the knowledge limitation of the specialist consultant to interpret the data (Stoorvogel and Bouma, 2005). In Nebraska, USA, a PA cropping consultant found that even with an average marginal profit of US$30 $acre^{-1}$ through the use of SSNM, it is very difficult to convince a producer that adoption of SSNM would give this same profit level his or her property (J. Crowfoot, pers comm.).

While most economic evaluations are based on partial budgeting and financial analyses, the large indirect benefits accruing from meeting environmental requirements, achieving traceability and the factoring in of the 'value of

information', have proven difficult to quantify (Tihomir et al., 2005). Smidt et al. (2000) concluded that the likelihood of a positive return on SSNM was greater as the value of the crop increased (e.g. potatoes > winter wheat) and where environmental costs (e.g. tax on N losses) were included in the economic modelling. They also noted that many linear models fail to account for: carry-over effects of increased soil N from one year to the next; improved quality of product where this occurs; and the beneficial effects of simultaneously managing several inputs with SSNM technologies, rather than just the one being studied in the modelling exercise.

Pannell (2004) investigated the economic gains that can be made through implementation of PA strategies. Whereas implementation of a new farming concept (e.g. SSNM) can often result in a substantial improvement in profit, the additional cost required to carefully determine the *exact* level of inputs needed to optimise profit will often far exceed the marginal gain in pay-off. This is because the optimum response is often located within the flat 'pay-off' part of the response curve. Consequently, the greatest response to lime is from the first tonne applied, and that beyond the optimum input of 2.1 t/ha, further gain in gross margin is negligible (Pannell, 2004). For low-cost inputs such as lime, the cost of accurately defining the optimum lime requirement will likely far exceed the small profit gain that might result. In this and many other cases, acknowledging the flatness of the profit curve is of far greater significance to practitioners than the identification of the optimum input level (Pannell, 2004). Often, input levels +/- 20 - 30 % of optimum may have no significant effect on production, especially given the uncertainty that surrounds the data used to predict response curves.

Pannell (2004) also showed that while it is known that there is wide aversion to risk taking amongst the farming community, incorporating risk into economic models had almost no impact on profit, mainly because any changes in levels of input were, again, likely to be in the flat part of the pay-off curve. Thus, science that aims to determine the *shape of the response curve* to (an) input(s) may be of greater value than science that sets out to more carefully define the *optimum* input level, unless such work is required to meet environmental or regulatory requirements.

Conclusions

Application of SSNM provides a means whereby rates and timing of fertiliser applications and types of fertiliser can be matched to optimise crop and pasture growth requirements, with minimal nutrient loss to the environment.

- Adoption has been poor because marketing has emphasised efficiency of nutrient use to generate profit. Examples of increased profit are few, but once environmental requirements, market access and social considerations become factored into the analyses the need for and use of SSNM tools will likely increase dramatically.
- Improved and new on-the-go sensors to determine resource condition will assist farmers in developing LMU maps of their farms.
- Expensive, high-tech mapping of variation in resource condition and yield is not always necessary for developing SSNM plans. Simple methods have been shown to be very cost effective and environmentally beneficial in grazed pastures and plantations. Numerous developments are becoming available that may increase the ease, and decrease the cost of data collection, critical to developing SSNM plans.
- Special consideration is needed to develop technologies appropriate for routine use in developing countries where farms are small and discretionary money is scarce. This will require technologies and concepts applicable to these agriculture systems; greater sharing of existing data; provision of technical and educational assistance to train staff farmers respectively; and the availability of open-source software, where needed. Education, through group meetings, of low cost SSNM methods will improve efficiency of nutrient use.
- A large impediment to adoption of SSNM technologies appears to be the poor, or even lack of integration and communication amongst basic and applied scientists, technology developers, agronomic and financial consultants, sales people and the practical farmer who must pay for, use, and require positive economic and/or environmental returns from use of the technology. Without a multi-disciplinary development approach that includes end-users, SSNM will not live up to expectation.
- If used pro-actively by producer organisations, these technologies could provide a solid base from which to negotiate the imposition of 'realistic' environmental limits on land use, that is supported by scientific data, to show improved outcomes through use of SSNM.

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