Dawson, A. & Knowles, O., 2018. To grid or not to grid – a review of soil sampling strategies. In: Farm environmental planning – Science, policy and practice. (Eds L. D. Currie and C. L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 31. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 10 pages

TO GRID OR NOT TO GRID
– A REVIEW OF SOIL SAMPLING STRATEGIES

Aimee Dawson and Oliver Knowles

Ballance Agri-Nutrients, 161 Hewletts Road, Mount Mangaunui
Email: aimee.dawson@ballance.co.nz

Abstract

Soil sampling assesses the nutrient status of the soil from which fertiliser and lime recommendations can be made. Spatial variability of soil fertility between and within paddocks can lead to over and under fertilisation. Traditional soil sampling treats paddocks as homogenous areas of similar soil fertility. More detailed sampling strategies such as all paddock, grid and directed soil sampling aim to look at soil fertility spatially with the aim to improve the return on investment of crop yield or pasture production. This review looks at the advantages and disadvantages of traditional, all paddock, grid and directed soil sampling and aims to identify opportunities for each strategy to be used. The authors conclude that when deciding which strategy to use the variability in soil fertility, maximum crop/pasture yield and crop/pasture value need to be considered.

Introduction

The growing and harvesting of pasture and crops and the removal of animal products off farm, removes nutrients from the soil. These nutrients need to be replaced to ensure soil test levels (and therefore yields) are not reduced over time. The removal of nutrients, as well as the replacement of nutrients through fertiliser spreading and animal nutrient transfer, is not uniform across a paddock or farm (Mallarino & Wittry, 2004). This leads to spatial variability in soil fertility. Blanket fertiliser applications across farms can lead to excessive fertilisation of some areas and under fertilisation in others (Brouder and Lowenberg-DeBoer, 2000; Cook and Bramley, 2000). Therefore, the variability in soil fertility needs to be considered by farmers and consultants when deciding soil sampling strategies.

Soil sampling assesses the nutrient status of the soil, giving paddock-specific information on soil fertility from which base fertiliser and lime applications are made (Edmeades *et al*. 1985; Flowers *et al*. 2005; Tan, 2005). In addition, the re-occurrence of soil sampling each year allows the nutrient status to be monitored over time. Soils are a biological system therefore changes and differences in nutrient status can occur temporally as well as spatially (Roberts *et al*. 1987; Roberts *et al*. 2011). Traditionally, soil sampling was completed by creating a composite paddock sample which was representative of a land management area on farm. However, more recently there has been a shift towards more intensive sampling such as all paddock sampling, grid soil sampling and direct/zonal soil sampling. This has been driven by the variability in soils and nutrient transfer by animals, which can alter the nutrient status between and within individual paddocks. Detailed soil sampling strategies aim to improve the return on investment (ROI) on fertiliser expenditure by varying the rates of fertiliser or lime. The ROI on the different soil testing strategies will be based on three factors; deficiency of nutrients, maximum crop yields and crop value (van Raij *et al*. 2002).

The aim of this review paper is to compare and contrast the “traditional” soil sampling method against all paddock, grid soil sampling and direct/zonal soil sampling. Determining benefits and disadvantages as well as providing a decision support tree to determine which method would suit varying situations.

“Traditional” Soil Sampling

The traditional soil sampling approach has been to treat paddocks as homogenous areas (Cline, 1944; Flowers *et al*. 2005; Tan, 2005), taking composite samples, consisting of 15-25 soil cores, which represents a land management area or block on farm (Troeh and Thompson, 1993). Land management areas are selected based on soil type, topography and management (Brown, 1993; FANZ, 2014). The paddock or block soil test gives an indication of the fertility of that land management area, from which tailored fertiliser or lime recommendations are developed. These paddocks are referred to as “monitor paddocks” and are soil tested every 1-3 years, at the same time, along the same transect (FANZ, 2014). With the development of global positioning systems (GPS) in the mid-nineties, these transects were able to marked with GPS to ensure that the soil tests were taken along the same transect every year. This is now considered good practice.

The assumption of traditional soil testing is that the analysis of the composite sample will give the same result as if each of the individual samples were analysed and averaged (Tan, 2005). Some authors suggest that composite sampling should only account for a maximum of 1 ha (Tan, 2005), 4 ha (Troeh and Thompson, 1993) or 8ha (Peck and Metsted, 1973). However, if areas are thought to be more homogenous then a composite sample can represent a larger area.

Traditional soil testing aims to take an average of the paddock, avoiding nutrient “hotspots” such as stock camps, gateways and urine/dung patches (FANZ, 2014) as well as unusual areas such as low wet spots, areas near roads and rocky out crops (Troeh and Thompson, 1993). Using the traditional soil sampling strategy will give an indication of the soil fertility and when looked at in combination with the soil test history can determine trends over time.

Advantages

Traditional soil testing is cost effective, with only one or two test per management area on farm required. Monitor paddocks are tested annually or biennially with additional paddocks added in such as crop paddocks and poorer performing paddocks. Some farmers may look to sample a portion of their property one year and another portion the following year until all of the paddocks have been sampled over a 3-4 year cycle (Brown, 1993). Therefore, over time a good picture is built on the farms overall fertility. Trend analysis is important for traditional soil testing and it is imperative that annual soil tests are not looked at in isolation. The aim of traditional soil testing is to increase the average soil fertility rather than create an even soil fertility across the farm.

Disadvantages

Since soils on farms vary, all areas within a paddock or block struggle to be fairly represented by a composite soil test result. The less homogenous the block area is the more likely there will be sampling errors (Tan, 2005). The composite sample results mask scattered areas of both higher and lower levels of soil nutrients within the block and paddock (Peck and Melsted, 1973). If nutrient status is highly variable, then a substantial portion of the paddock or block might respond to lime or fertiliser applications or both, even though a composite sample suggests no response.

When to use

Traditional soil testing can be used where there is:

- a good soil testing history,
- similar long term farm/nutrient management,
- paddocks have not been reformed during farm development,
- minimal variability in nutrient status and
- soil test transects are well established.

All paddock testing

Traditional soil testing only looks to test monitor paddocks that represent land management areas across the farm. All paddock testing (APT), tests all paddocks on the farm with the aim to understand individual paddock soil fertility, give a better indication of fertiliser requirement (Brown, 1993) and ultimately reduce variability of soil fertility between paddocks (Bowie and Venter, 2015; Roberts *et al*. 2011). All paddock testing identifies the individual paddock soil fertility allowing tailored recommendations, sometimes paddock specific, to occur. All paddock testing will ultimately give a more accurate assessment of soil fertility of the farm or block because of the increase in soil samples (Cline, 1944).

Advantages

All paddock testing gives the full range of soil fertility on farm so that tailored fertiliser recommendations can occur. Often capital rates of nutrients are required on some paddocks, while others that are well above optimum values, may have fertiliser applications withheld for a period. Roberts *et al*. (2011) found for a 96.4ha South Taranaki Dairy Farm that fertiliser expenditure was only 20% of the cost of blanket fertiliser applications when all paddock testing and more tailored fertiliser applications occurred. The ROI on all paddock testing will depend on the difference in soil fertility, with greater variance between paddocks having a larger ROI (van Raij *et al*. 2002).

Environmentally, identifying high fertility paddocks means that soil test values, especially phosphorus (P), can be mined down to more optimum levels. This decreases the risk of P run-off, which can have adverse effects if it enters waterways.

Disadvantages

All paddock testing, similar to traditional soil testing, makes the assumption that each paddock has a homogenous soil fertility. However, the assumption is that by enclosing a paddock by a fence this determines homogeneity (Peck and Melsted, 1973). All paddock testing results in a higher cost of testing due to a larger sample size (Brown, 1993). However, this may be offset by decreased fertiliser expenditure. Annual APT, will result in a higher cost to the farmer, as the returns of saving on fertiliser expenditure will be diminished as the soil fertility becomes more even.

When to use

All paddock testing is beneficial for farmers who do not have a good history of soil testing or have altered paddock layout through development or farm conversion. The authors suggest that using a mixture of APT and traditional soil testing will allow farmers to build a good picture of soil fertility on their properties.

Grid soil sampling

Grid soil sampling is a detailed analysis of in-paddock soil fertility. Describing nutrient variability across a paddock was difficult until the introduction of GPS and geographic information systems (GIS) (Flowers *et al*. 2005). Grid soil sampling uses GIS and GPS technology to accurately map soil sampling locations to create prescription maps, indicating soil fertility, which can then be used for variable rate (VR) spreading of fertiliser. There are two methods of grid soil sampling, cell sampling and point sampling.

Cell Sampling

Cell Sampling is the most straightforward sampling strategy. A cell is a subunit of a whole field. Soil cores (10-15 cores) randomly collected from locations throughout a cell are mixed to generate a composite sample for the cell. The resulting lime and fertiliser rates will be applicable to this entire cell. The entire field is represented by a checkerboard pattern of different recommendation rates.

Point Sampling

Point sampling is better for detecting patterns of paddock variability because all core samples are collected near georeferenced points (located at grid line intersections), rather than scattered throughout the cell. Soil test parameters are calculated between sampling points, which permits the construction of contour maps of each soil test parameter. For point sampling the closer the sample point spacing the more reliable the mathematics and interpolation between the soil testing points, because of this there has been much discussion around the appropriate grid spacing (Flowers *et al*. 2005; Franzen and Peck, 1995; Wallenhaupt *et al*. 1994). Franzen and Peck (1995) recommend that grid density should be decided by the uniformity of the field, soil types, past management and perceived economic benefit.

Advantages

Both cell and point sampling provide a detailed look at within paddock soil fertility. With the use of VR fertiliser spreading prescribed to the variability in soil fertility, the ideal result would be a more even pasture or crop growth, increased yield and more efficient use of fertiliser (Rossato *et al*. 2015). The ROI for grid sampling will depend on the increase in yield or production and the value of that pasture/crop (Swinton and Lowenbery-DeBoer, 1998). High value crops would be more likely to see a return from grid sampling providing the variability of soil fertility was sufficient and the VR spreader could spread product accurately to the prescription map (Holmes and Jiang, 2017).

Disadvantages

Grid soil sampling has been described as cost and labour intensive (Fleming *et al*. 2000; Nanni *et al*. 2011; Stamper *et al*. 2014; van Raij *et al*. 2002). In addition, there is disagreement in the literature around appropriate grid size to give a full understanding of the variability in soil fertility (Fleming *et al*. 2000; Flowers *et al*. 2005; Franzen and Peck, 1995; Hammond, 1993; Nanni *et al*. 2011; Rossato *et al*. 2015; Stamper *et al*. 2014; Wollenhaupt *et al*. 1994). Stamper *et al*. (2014) states that the "sampling density or grid size as well as the method of aggregation can alter the nutrient management decision". In most cases, the higher the resolution the more realistic the representation of soil fertility (Schepers *et al*. 2000). However, with increased resolution the greater the sampling cost. Flowers *et al*. (2005) suggests that the optimal grid size to sample a field may not be known until after the sampling has occurred.

The ROI of the grid sampling is variable due to the variability in the soil fertility extremes within paddocks. Therefore, the returns from decreasing soil fertility variability needs to be determined (van Raij *et al*. 2002). In most situations, determining the soil pH will be most cost effective as it is one of the most spatially variable soil characteristics and effects the availability of nutrients (Bongiovanni and Lowenberg-DeBoer, 2000; Cline, 1944).

When to use

Grid soil sampling will have the most benefit in paddocks where there is assumed to be large variability in soil fertility and therefore by VR fertiliser spreading an increase in crop yield will be seen. For example, where previous management altering the soil fertility has caused variability, paddocks with different cropping histories have been merged or where stock camps/grazing differences occur.

Directed Sampling

Directed sampling is referred to within the literature as zonal sampling, point sampling and targeted sampling. For this paper, directed sampling will be used.

Peck and Melsted (1973) state the first step of a sound soil sampling procedure is to subdivide the area into homogenous units. Directed sampling aims to identify homogenous areas that have similar yield limiting factors through an understanding of paddock variability (Buttafuoco *et al*. 2009). Crop growth and yields vary due to a number of factors. Some of these are inherent soil properties (soil texture, drainage, etc.), and some are due to land management history (treading damage, land shaping, spreader patterns, previous land use, animal transfer etc.). Directed soil sampling zones can be created by soil maps (Wibawa *et al*. 1993) yield mapping (Flowers *et al*. 2005), aerial footage of crops (Fleming *et al*. 2000), digital elevation maps (DEM), electrical magnetic (EM) maps or soil series maps (Mallarino and Wittry, 2004). Clay and soil organic matter content as a proxy for soil type has also been used (Rossato *et al*. 2015). Creating homogenous zones within a paddock reduces the number of samples while still recognising areas of differing nutrient status. Direct sampling of homogenous sub regions within a field has been shown to give similar results to grid sampling, but with less cost in developing the prescription map due to lower sampling and labour costs (Fleming *et al*. 2000; Flowers *et al*. 2005).

Traditional soil testing may show soil fertility is within optimum, however there may be noticeable growth differences within a paddock. Soil testing different zones of the paddocks, such as fronts and backs, can determine if there is a difference in soil fertility, which can then be remediated. This is becoming more common in Canterbury, where long rectangular or pie shaped paddocks, developed for ease of irrigation, are causing nutrient distribution towards the front half of the paddock where stock tend to camp. Soil testing these separately can result in VR spreading to these paddock areas to create a more even pasture growth and better fertiliser utilisation.

Advantages

Directed sampling requires fewer samples compared to grid sampling, therefore there is a lower sampling cost for farmers (Flowers *et al*. 2005; Mallarino *et al*. 2004). However, for directed sampling there is a greater requirement on knowledge and understanding of the potential for differences in soil fertility by the consultant or farmer to determine soil testing zones. In addition, other mapping such as EM, soil or yield mapping may be required before zones can be recognised. There can be savings made on fertiliser expenditure for directed sampling, providing that the soil fertility between the zones are significantly different (Robertson *et al*. 2008).

Disadvantages

Directed sampling requires the consultant to have an in-depth knowledge of the farm and the potential for differences in soil fertility, or creation of an EM or yield map prior to soil sampling. Furthermore, the formation of a composite sample per zone means that differences in soil fertility within that zone may be missed. This is similar to the constraints around traditional soil sampling. However, in contrast to directed sampling, traditional sampling allows the analysis of trends over time to build a larger picture of on farm soil fertility.

When to use

Directed sampling is a more detailed look at in-paddock differences compared to traditional and APT. However, is less detailed than grid soil sampling. Directed sampling could be better suited to pasture/crops that have a lower return, where the cost of grid sampling would not be returned based on the additional crop/pasture growth, and where the consultant or farmer could delineate zones within a paddock.

Discussion and Conclusion

Soil sampling is an integral part of best practice nutrient management (Stamper *et al*. 2014). Farmers and their consultant must decide on which sampling strategy will give the greatest return.

All paddock testing found significant fertiliser savings in a South Taranaki Dairy Farm in New Zealand compared to traditional soil sampling (Roberts *et al*. 2011). However, analysis of the overall savings and ROI of doing more detailed sampling for a broader range of farms is limited. Directed sampling has been found to give similar soil fertility information as coarse grid sampling but with reduced sampling costs (Mathews *et al*. 1999; Schepers *et al*. 2000). Directed sampling also gives a greater improvement in the knowledge that variability of soil fertility exists within the paddock compared to traditional soil sampling. This may allow the farmer to explore what may be causing the variability over time. Creating zones for directed soil sampling requires additional information on where the variability in soil fertility might occur, for example yield or EM maps.

Studies comparing differing soil sampling strategies found that directed sampling was more accurate for developing a VR fertiliser prescription map for phosphorus (P) and potassium (K) compared to cell sampling (Wollenhaupt *et al*. 1994). In contrast, Mallarino and Wittry (2004) found in crop paddocks, when comparing grid and directed sampling, that grid sampling was most effective for P (as it was the most variable nutrient). In addition, directed sampling was more effective for soil pH and both strategies were similarly effective for K levels. Furthermore, Mathews *et al*. (1994) found in rotationally grazed pastures, zonal sampling (using contour maps), gave a similar indication in K variation compared to grid soil sampling. However, this was probably due to stock nutrient transfer to stock camps that were easily delineated. van Raij *et al*. (2002) suggests that if the conditions which are known to effect yield are identified then testing fixed sites rather than a complete grid will give sufficient detail. These papers demonstrate that there is no sampling approach that is best at understanding the variability within paddocks for all soil tests.

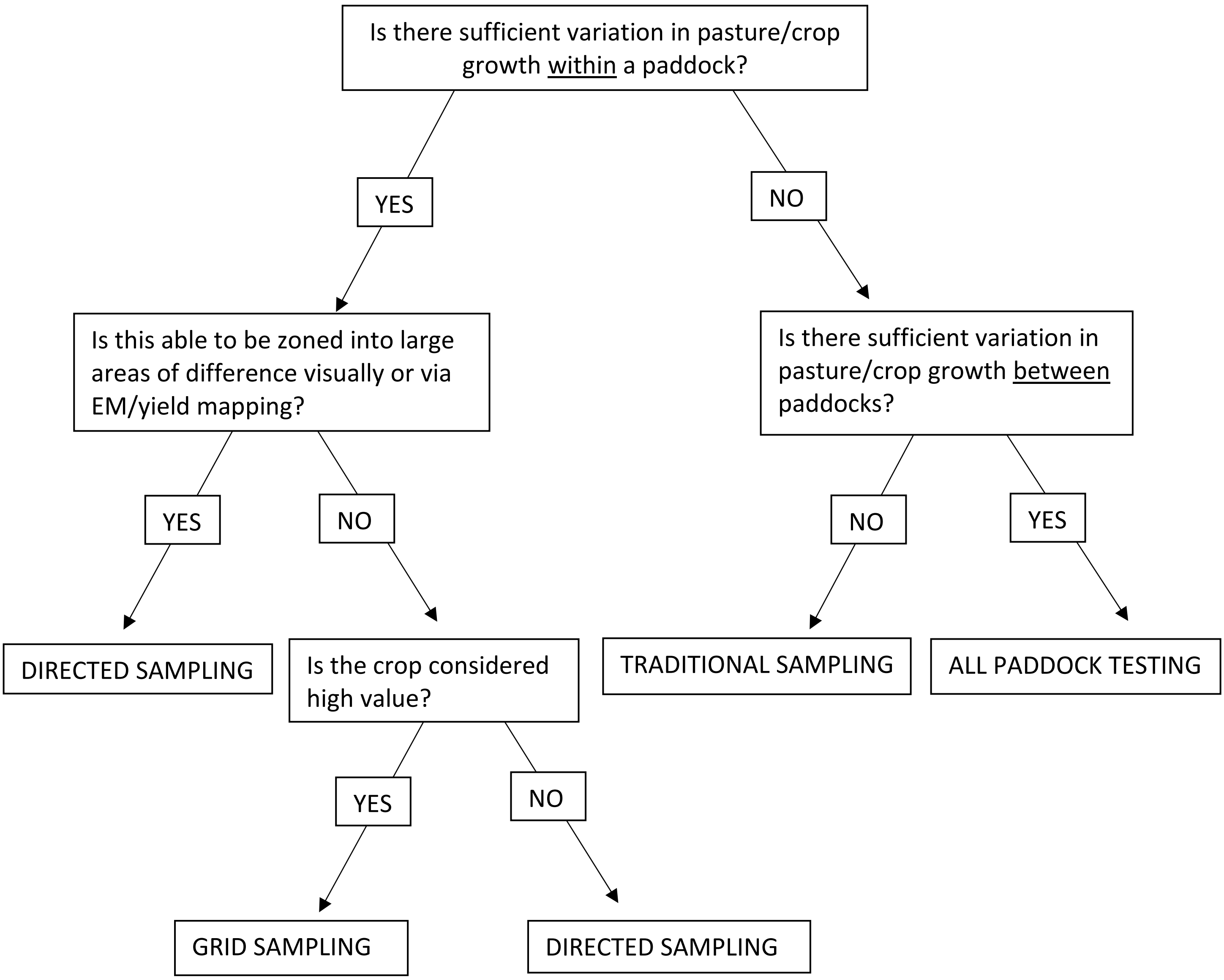

Figure 1: Decision support tree to determine best fit for soil sampling strategies

When deciding which strategy to use, it is important to consider the costs of sampling, paddock history, likely responses of crops/pasture to fertilisation and therefore the overall ROI. Furthermore, understanding the appetite for the farmer to alter his soil testing and therefore fertiliser programme is imperative. van Raij *et al*. (2002) suggests that ROI will be greater if you can obtain higher yields from in depth soil testing rather than fertiliser saving. Similar amounts of fertiliser may be used but instead are redistributed within a paddock (Brouder and Lowenberg-DeBoer, 2000). Wibawa *et al*. (1993) found that yields of wheat and barley were higher where grid sampling and VR fertiliser was used. However, when the cost for the more intensive grid sampling was accounted for the net return was less than traditional soil testing and fertiliser applications. This indicates that crop value must be considered rather than yield alone. For high value crops, where response to additional fertilisation can be significant, then more intensive sampling such as grid or directed sampling may be beneficial (Swinton and Lowenbery-DeBoer, 1998). In addition, the soil test may only consider one specific nutrient or pH where a yield response will be seen or where known variability in this test is known.

Traditional, all paddock, grid and directed soil sampling each have a position within soil sampling strategies on farm. From the literature review, a decision support tree (Figure 1) was created to aid farmers and consultants on which sampling method to use. Farmers and consultants need to determine the ROI of each of the specific strategies determining the variability of crop/pasture yield, maximum crop yield, value of the crop and most importantly the farmer's willingness to change to a more intensive sampling strategy. Soil sampling strategies could work in combination or in gradual progression, from traditional to all paddock to directed to grid, and at each step analysis of the variability and ROI determined. Previous information can be utilised to determine if sufficient variability has occurred before increasing the resolution of soil samples and therefore the cost of sampling.

Recommendations for further work

Future work on comparison and ROI for differing soil sampling strategies is required, especially in a New Zealand context. Research papers are lacking in different crops, nutrients and soil types, with a focus on on-farm decision making. Currently, in New Zealand there is no agreed protocol on agricultural grid soil sampling. In addition, there is no "minimum variability" in soil tests to help support the decision making around differing soil sampling strategies and when VR spreading could increase yield or pasture production.

References

Bongiovanni, R. and Lowenberg-DeBoer, J. (2000). Economics of variable rate lime in Indiana. *Precision Agriculture*. **2:** 55-70.

Bowie, S.A. & Venter, H.J., 2017. Whole Farm Testing: A further review of data. In: Science and policy: nutrient management challenges for the next generation. (Eds L. D. Currie and M. J. Hedley). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 30. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 5 pages.

Brouder, S. and Lowenberg-DeBoer, J. (2000). Managing long-term soil fertility. In J. Lowenberg-DeBoer and K. Erickson. Precision Farming Profitability. Purdue University, USA.

Brown, A.J. (1993). A review of soil sampling for chemical analysis. *Australian Journal of Experimental Agriculture.* **33:** 983-1006.

Buttafuoco, G., Castrignano, A., Colecchia, A.S. and Ricca, N. (2009). Delineation of management zones using soil properties and a multivariate geostatistical approach. *Italian Journal of Agronomy*. **4**: 323-332.

Cook, S. E. and Bramley, R. G. V. (2000). Coping with variability in agricultural production - implications for soil testing and fertiliser management. *Communications in Soil Science and Plant Analysis*. **31**: 1531-1551

Cline, M. (1944). Principles of soil sampling. *Soil Science*. **58**: 275-288.

Edmeades D.C., Cornforth I.S. and Wheeler D.M. (1985). Getting maximum benefit from soil testing. *New Zealand Fertiliser Journal*. **67:** 16-17.

Fertiliser Association of New Zealand (FANZ). (2014). Fact Sheet 2 - Soil and Plant Testing. Code of practice for nutrient management. Retrieved from: http://www.fertiliser.org.nz/Site/code_of_practice/fact_sheets/default.aspx

Fleming, K.L., Westfall, D.G. and Bausch, W.C. (2000). Evaluating management zone technology and grid soil sampling for variable rate nitrogen application. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), Proceedings of the 5th International conference on precision agriculture and other source management.

Flowers, M., Weisz, R. and White, J.G. (2005). Yield-based management zones and grid sampling strategies: describing soil test and nutrient variability. *Agronomy Journal*. **97**: 968-982.

Franzen, W.D., and T.R. Peck. (1995). Field soil sampling density for variable rate fertilization. *Journal Production Agriculture*. **8**:568-574.

Hammond, M.W. (1993). Cost analysis of variable fertility management of phosphorus and potassium for potato production in central Washington. p. 213-228. In: P.C. Robert *et al*. (ed.). Soil-Specific Crop Management. ASA, SSSA, ASA. Madison, WI.

Holmes, A.W. and Jiang, G. (2017). Effect of variable rate lime applications on autumn sown barley performance. *Agronomy New Zealand.* **47:**37-45.

Mallarino, A.P. and Wittry, D.J. (2004). Efficacy of grid and zone soil sampling approaches for site-specific assessment of phosphorus, potassium, pH and organic matter. *Precision Agriculture.* **5:** 131-144.

Mallarino, A.P., Beegle, D.B. and Joern, B.C. (2006). Soil sampling methods for phosphorus – spatial concerns. A SERA-17 position paper. Southern Education Research Activites (SERA) 17, United States Department of Agriculture.

Mathews, B. W., Sollenberger L. E., Nkedi-Kizza P., Gaston L.A., and Hornsby H. D. (1994). Soil sampling procedures for monitoring potassium distribution in grazed pastures. *Agronomy Journal*. **86**:121-126

Mathews, B.W., Tritschler, J.P., Carpenter, J.R. and Sollenberger, L.E. (1999). Soil macronutrient distribution in rotationally kikuyu grass paddocks with short and long grazing periods. *Communications in Soil Science and Plant Analysis.* **30**: 557-571.

Nanni, M.R., Povh, F.P., Demattê, J.A.M., de Oliveira, R.B., Chicati, M.L., Cezar, E. (2011). Optimum size in grid soil sampling for variable rate application in site-specific management. *Scientia Agricola.* **68***:* 386-392.

Peck, T.R. and Melsted, S.W. (1973). Field Sampling for Soil Testing. In Walsh, L.M. and Beaton, J.D. (Eds). Soil Testing and Plant Analysis. Published by Soil Science Society of America. USA.

Roberts, A.H. (1987). Seasonal variation in soil tests and nutrient content of pasture at two sites in Taranaki. *New Zealand Journal of Experimental Agriculture.* **15**: 283–294.

Roberts, AH., White, M., Lawrence, H. and Manning, M. (2011). When More is More – A Prècis! In: *Adding to the knowledge base for the nutrient manager*. (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 5 pages

Robertson, M., Lyle, G., and Bowden, J. W. (2008). Within-field variability of wheat yield and economic implications for spatially variable nutrient management. *Field Crops Research.* **105:** 211-220.

Rossato, O.B., Cruscoil, C.A.C., Guerra, S.P.S. and Zimback, C.R.L. (2015). Implications of soil sampling processes on recommendations of phosphate and potassium fertilizers on sugarcane. *Engergia Na Agricultura*. **30**: 109-118.

Schepers, J.S., Schlemmer, M.R. and Ferguson, R.B. (2000). Site-Specific Considerations for Managing Phosphorus. *Journal of Environmental Quality*. **29**: 125-130

Stamper, D.J., Agouridis, C.T., Edwards, D.R. (2014). Effect of soil sampling density and landscape features on soil test phosphorus. *Applied Engineering in Agriculture*. **30**: 773-781.

Swinton, S.M. and Lowenberg-DeBoer, J. (1998). Evaluating the profitability of site-specific farming. *Journal of Production Agriculture*. **11**: 439-446.

Tan, K.H. (2005). Soil Sampling, Preparation and Analysis (2nd Edition). Published by Taylor & Francis Group, USA. ISBN 0-8493-3499-3

Troeh, F.R. and Thompson, L.M. (1993). Soils and Soil Fertility (5th Edition). Published by Oxford University Press, New York. ISBN 0-19-508328-8

van Raij, B., Cantarella, H. and Quaggio, J.A. (2002). Rationale of the economy of soil testing. *Communications in Soil Science and Plant Analysis.* **33:** 2521-2536.

Wibawa, W.D., Dludlu, D.L., Swenson, L.J., Hopkins, D.G and Dahnke, W.C. (1993). Variable fertilizer application based on yield goal, soil fertility and soil map unit. *Journal of Production Agriculture*. **6:** 255-261.

Wollenhaupt, N.C., Wolkowski, R.P. and Clayton. M.K. (1994). Mapping soil test phosphorus and potassium for variable-rate fertilizer application. *Journal of Production Agriculture.* **7**: 441-448.