Drewry, J.J., Cavanagh, J.E., McNeill, S., Taylor, M.D. 2018. Long term monitoring of soil quality including trace elements in the Wellington region. 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. 11 pages.

LONG-TERM MONITORING OF SOIL QUALITY INCLUDING TRACE ELEMENTS IN THE WELLINGTON REGION

JJ Drewry[1], JE Cavanagh[2], S McNeill[2] and MD Taylor[3]

[1] *Greater Wellington Regional Council, PO Box 41, Masterton*
(Now at Manaaki Whenua Landcare Research, Private Bag 11052, Palmerston North)
[2] *Manaaki Whenua Landcare Research, PO Box 69040, Lincoln*
[3] *Waikato Regional Council, Private Bag 3038, Waikato Mail Centre, Hamilton*

Abstract

There is increasing competition between the demand for land functions that provide food, water, and energy, and those services that support and regulate life cycles. There can also be increased risk of losses of contaminants and nutrients to water bodies. Recent policy initiatives, such as fencing stream margins by regional councils, can mitigate some nutrient and contaminant losses. Several recent studies, however, show that current stream fencing policy alone may not be sufficient to improve water quality.

The monitoring of soil quality provides evidence for determining the effectiveness of planning and implementation for environmental protection, and acts as an early warning system. Soil quality is therefore an essential link to nutrient and contaminant source and farm practice, and to inform policies to improve farm management and water quality. With the exception of two recent studies that reported on soil quality monitoring for up to 20-year periods in the Auckland and Waikato regions, few studies have reported on soil quality and trace element monitoring over the long-term in New Zealand or internationally.

This paper reports on the indicators Olsen P (phosphorus) and cadmium from soil quality and trace element monitoring over a period of 18 years (2000–2017 inclusive) in the Wellington region of New Zealand. Specifically, we looked at how key indicators changed over this period, and how they were affected by land use. We report on Olsen P (phosphorus) and develop a statistical modelling approach to evaluate trends over time. We then test the approach used for evaluating cadmium to assess the utility of the approach for other indicators.

Introduction

Land provides food, water, energy, and services that support and regulate life cycles, but there is increasing competition between these demands and land functions. Pressures on land include application of contaminants and nutrients, the effects of which can include reduced provisioning, regulating and cultural services. There can be increased risk of losses to water bodies, contributing to changes in the composition of biological communities or impact on human and animal health.

Recent implementation of policy initiatives such as fencing stream margins by regional councils can mitigate some nutrient and contaminant losses. McDowell et al. (2017), however, show that current New Zealand stream fencing policy initiatives may not be sufficient to adequately reduce nutrient loads in catchments. That study indicates that pastoral low-order small streams currently exempt from fencing regulations account for large percentages of the national total N and dissolved reactive P loads. Mitigations such as reducing nutrients at the source (rather than edge-of-field) are likely to be more cost-effective than mitigations further away from the source (e.g., McDowell et al. 2015, 2017).

Soil quality is therefore an essential link to water quality. It can be a factor in the source of nutrients and contaminants, or affect transport to water such as through increased overland flow from compacted soil. Soil nutrient concentrations above soil optimum guidelines, for example, can increase the risk to water quality (e.g. Burkitt et al. 2010; Hart & Cornish 2016). Soil quality is therefore important in farm nutrient budgeting and planning farm and catchment mitigation strategies and policy to improve water quality.

Monitoring of soil quality provides evidence for determining the effectiveness of planning and implementation for environmental protection, and acts as an early warning system for emerging issues. The effects of land use, management, and soil type on soil quality indicators can vary (e.g. Houlbrooke et al. 2008; Taylor et al. 2010; Fernandez et al. 2012). Soil quality indicators including trace elements are regularly monitored by New Zealand regional authorities in State of the Environment monitoring using standard methods. Diffuse source trace elements are an important component of the monitoring. Sources include current or historic use of pesticide sprays, animal remedies, veterinary medicines, or fertiliser application (e.g. cadmium). Some sites have accumulated trace element levels above soil guidelines (e.g. Cavanagh 2014; Curran-Cournane 2015).

Only a few studies have reported on long-term soil quality monitoring in New Zealand or internationally (Cavanagh et al. 2017). Recent monitoring studies include, for example, soil quality in Tasmania (Cotching & Kidd 2010), while Curran-Cournane (2015) and Taylor et al. (2017) reported on soil quality monitoring over 15 and 20 year periods in the Auckland and Waikato regions, respectively.

This paper reports on soil quality monitoring over an 18-year period (2000–2017 inclusive) in the Wellington region. Specifically, we looked at how key indicators changed over this period, and how they were affected by land use. We report on Olsen P (phosphorus) and develop a statistical modelling approach to evaluate trends over time. We then test the approach used for evaluating cadmium to assess the utility of the approach for other indicators. We briefly discuss opportunities for improving regional and national reporting, and farm soil management.

Overview of soil quality indicators

The soil quality indicators typically monitored in soil quality monitoring programmes are pH, organic carbon, anaerobically mineralised N, hot water extractable carbon, and total nitrogen. Olsen P is an indicator of plant-available P. Trace elements may also be monitored, with As, Cd, Cr, Cu, Pb, Ni, and Zn the most commonly measured trace elements. Soil physical properties typically include macroporosity and field bulk density, which are indicators of compaction (Drewry et al. 2004).

Methods

Overview of monitoring programme

The monitoring programme was developed from a project monitoring sites across many regions of New Zealand (e.g. Hill et al. 2003; Sparling et al. 2004). Many councils continued and added sites and indicators that were standardised in a set of guidelines by the Land Monitoring Forum (Hill & Sparling 2009). In the Wellington region, soil quality monitoring data for this study were available from 2000 to 2017 inclusive. Sites were established from 2000 to 2003. Dairy, mixed cropping, and market garden persistent land use generally had five samplings per site over this period. Indigenous and forestry land uses had two samplings per site, and in most cases persistent drystock sites had three samplings.

Measurements

Details of field methods are reported in the Land Monitoring Forum report (Hill & Sparling 2009). Briefly, at each site 10 cm (2.5 cm diam.) depth soil cores were collected approximately every 2 m along a 50-m transect. Individual cores were bulked and mixed to obtain a representative sample. Soils were classified according to the New Zealand Soil Classification (Hewitt et al. 2010). Land use classes were used – see later section. Soil chemical measurements were analysed by Manaaki Whenua Landcare Research. Samples for trace elements were sampled as above. Total recoverable trace elements were analysed by Hill Laboratories in Hamilton. Olsen P was measured on a gravimetric (weight) basis by Manaaki Whenua Landcare Research and therefore avoids the confounding influence of field bulk density.

Guidelines

Soil quality indicators can be used to assess how land use influences soil for plant growth or for potential risks to the environment. For regional authorities, the target/guideline range for Olsen P was updated in Mackay et al. (2013). These guidelines focus on environment, so can have lower values than for some production-based uses, e.g. vegetable production. The guidelines from Mackay et al. (2013) for Olsen P in sedimentary soils are 20–40 mg/kg for mixed cropping, pasture, horticulture and market gardens, and 5–30 mg/kg for forestry. The hill country pasture guideline is 15–20 mg/kg.

Statistical analysis

Longitudinal (temporal) analysis

The analysis started with Olsen P to develop statistical models to assess temporal trend. These will be used as a basis to develop models for other indicators. All analyses were carried out using the statistical package ‘R’ version 3.4.1 (R Core Team 2017). To determine a temporal trend in which soil order was a potentially confounding factor, there were too few sites for Melanic and Allophanic soils so these were removed. Soil orders remaining in this analysis were Brown, Gley, Pallic, and Recent soils. Sites with only one measurement period were removed from the analysis. With these criteria, sites were reduced from 118 to 109 sites, then, with further reduction using the farm system criteria described below and removal of two outlier sites with large residuals, to 84 sites.

A focus in this analysis is how the indicators changed over time. There are several approaches. The indicator quantity changes first for absolute time (year), then for the differences in time between measurements. In the latter case, two sites sampled for the first time in different years would have the same starting time difference (a time difference of zero years), all other things being equal. In this paper, this latter time difference is the focus.

Farm system

Land use was based on the ‘persistent land use’ or ‘farm system’, which acknowledges the longer-term land use. One sampling of a site, for example, may have been in sheep-grazed pasture, but a later sampling may have been a temporary fodder crop as part of the same whole farm system. Therefore only sites with ‘farm system’ that were the same for all samplings in the period were used for this analysis. There were 23 sites with persistent land use change, so these were removed from the analysis. The farm system classification (with notes) used is: dairy (milking platform), drystock, (sheep, beef, deer, dairy runoff), forestry (exotic pine), horticulture (orchards, vineyards), indigenous (native bush or vegetation), market garden (intensive vegetables), and mixed cropping (extensive arable cropping often with pasture in the farm system).

Analysis

In a longitudinal analysis, repeated measurements of a site are made at different times. In this analysis, we assumed that the indicator has a level that depends on the soil order as a fixed effect and the site as a random effect. Olsen P data were log-transformed. For log-transformed gravimetric Olsen P, an initial model (*M1*) was fitted using a linear mixed model by residual maximum likelihood (REML). When checked for large deviations from normal distribution, several points anomalous compared with the rest of the data were removed to improve model fit, (model *M2*). Brown soils and indigenous land use were deemed to be the ‘reference’ level per analysis. However, as soil order had little effect it was later removed from the refined model (*M3*), which allowed for determination of for each land use and is reported below. The final adopted model, *M3* is:

$$\log \text{Olsen P}_{i,j} = \mu + S_i + L_j + \alpha_k . \Delta t + \epsilon_{ij} \quad (1)$$

In equation (1) above, the log-transformed Olsen P for site i and land use class j is modelled by an overall mean μ, a random effect for each site S_i, a fixed effect L_j for land use class j, and a linear trend α_j for land use j that depends on the change in time Δt from the reference date. The uncertainty of the model is accounted for in the error term ϵ_{ij}.

A similar analysis was then conducted for cadmium. Cadmium data were log-transformed. Values less than the limit of detection were replaced by half the value. Two additional outlier sites were removed.

Results

Longitudinal analysis – gravimetric Olsen P

Using model *M3* described above, the results for gravimetric Olsen P are presented.

Land use (farm system) effect

The mean level (“reference level”) of log-transformed gravimetric Olsen P at the first measurement, for indigenous land use is 3.1 (95% confidence interval [2.72, 3.47]). When back-transformed, this corresponds to an Olsen P value of 22.1 (95% CI [15.17, 32.27]).

These log values were back-transformed to multiplicative factors that are applied for each land use. The effects of land use (farm system) are shown in Figure 1, and are independent of soil order.

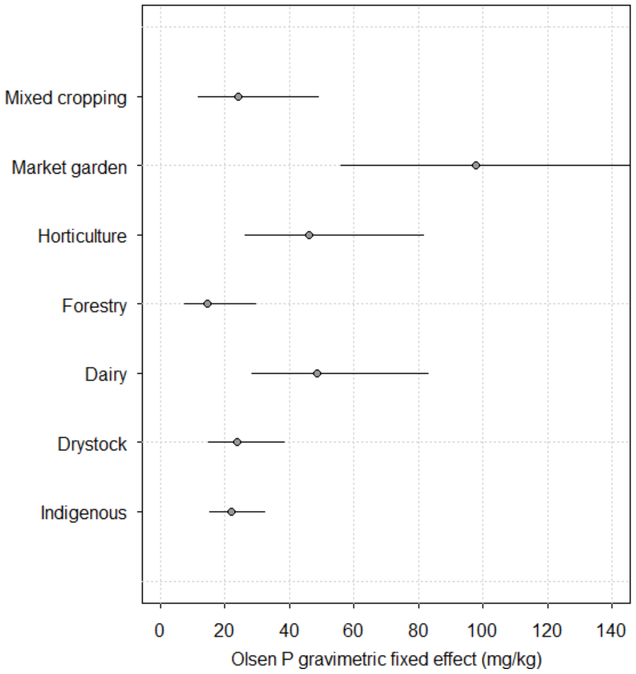

Figure 1: Land use fixed effects for Olsen P (mg/kg). The markers are the estimated mean from simulations. The lines represent plus-and-minus one standard deviation.

Temporal effect

The temporal effect was modelled using *M3* and is presented in Figure 2. The temporal effect depends on land use; for indigenous land use there is no significant difference from zero. The back-transformed multiplicative factors that are applied for each land use (farm system) are shown in Figure 2. Figure 2 shows that the greatest mean temporal change over the period was for forestry and mixed cropping. Note that the temporal change per year is presented.

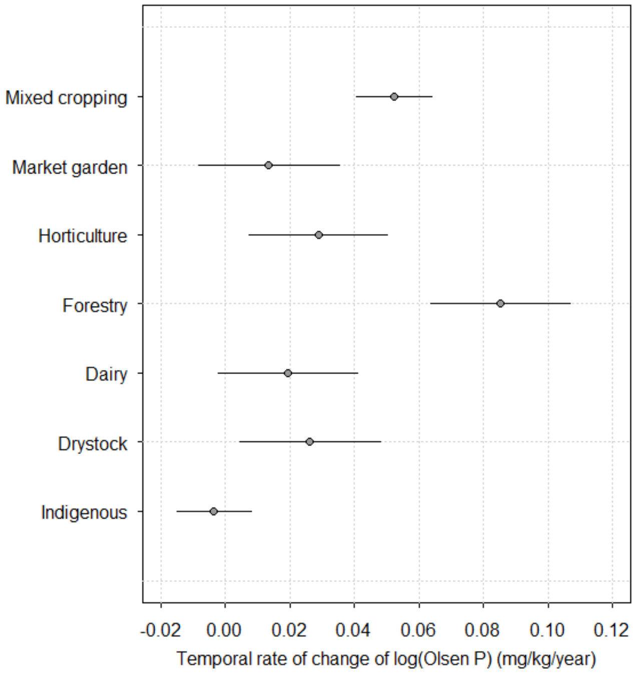

Figure 2: Estimated temporal rate of change of log (Olsen P mg/kg/year) by land use. The markers are the estimated mean from simulations. The lines represent plus-and-minus one standard deviation.

Guideline values

Mean Olsen P values for dairy, horticulture and market garden land uses are greater than the Land Monitoring Forum guidelines. Consequently, many individual site values exceed these guidelines, as shown in Figure 1. Details of the Land Monitoring Forum guidelines were presented in the methods sub-section ‘guidelines’.

Longitudinal analysis – cadmium

Land use (farm system) effect

The land use (farm system) effects for cadmium are shown in Figure 3. When back-transformed, the mean level of Cd for indigenous land use is 0.094 mg/kg (95% confidence interval [0.07, 0.126]).

Temporal effect

The temporal effect, which depends on land use, was modelled using *M3* and is presented in Figure 4. Figure 4 shows the estimates of the mean effect per year as markers, with lines indicating the 95% confidence interval. The result appears to show no evidence that the rate of change of log-transformed Cd concentration is different from zero for all land use classes except for horticulture. The analysis (data not shown) suggests that, as for Olsen P, the Cd temporal trend for dairy land use appears to show curvature centred around 2005–2010. This is probably only apparent because of the relatively large number of sampling points over time for the dairy class compared with other classes.

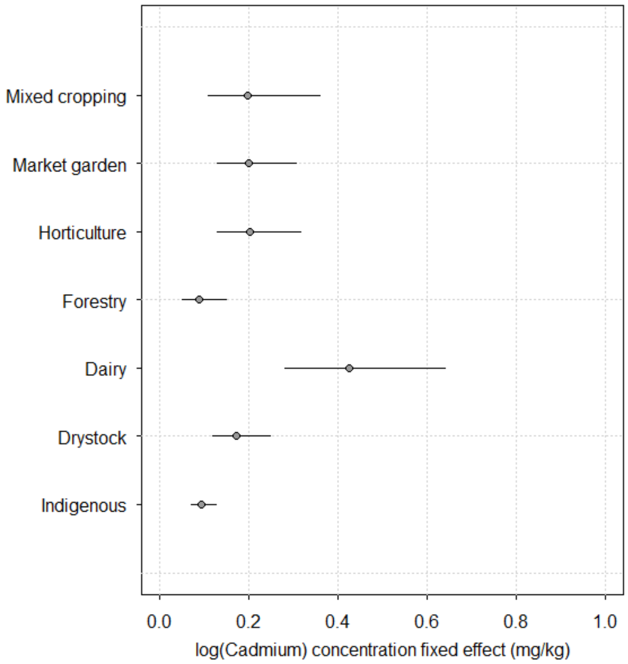

Figure 3: Land use fixed effects for Cd (mg/kg) by land use. The markers are the estimated mean from simulations. The lines represent the 95% confidence interval.

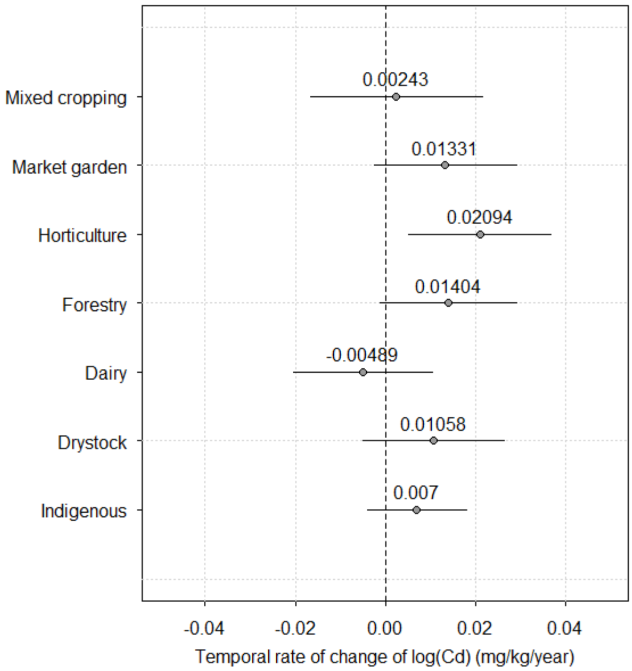

Figure 4: Estimated temporal rate of change of log (Cd mg/kg/year) by land use. The markers are the estimated mean from simulations. The lines represent the 95% confidence interval.

Discussion

Olsen P

Our study estimates the annual average change over time per land use, although there was high variation that may be reduced with the inclusion of data from a greater number of sites. It would therefore be useful in the future to combine data with several other regions and undertake further analysis to provide a more robust assessment of trends over time.

Surprisingly, the temporal change in Olsen P was greatest for the exotic forestry land use, but there were a limited number of sites and samplings. Soil phosphorus has been shown to increase at high tree densities in a long-term pine forestry trial in the Rotorua area (Hawke & O'Connor 1993). Nutrient cycling in forestry systems was indicated by Hawke and O'Connor (1993) to be efficient, with nutrient returns to soil from pine leaf litter or canopy leaching with reduced nutrient demand in the latter stages of the forest growth.

In a study of soil quality monitoring in the Waikato, Taylor et al. (2017) reported that Olsen P results showed a significant, non-linear, increasing pattern over time, and that some changes matched changes in world commodity prices.

Cadmium

The mean Cd concentrations for the land uses in this study were generally as expected from other studies using regional Cd monitoring data, with Dairy having the highest concentrations (Cavanagh 2014; Taylor et al. 2010). As with the Olsen P data, there is high variability in the results, which may mask any increases over time. Nonetheless, there was a significant increase in Cd for horticulture sites, and near-significant increases in forestry and market gardens land-use. We note that Cd data were reported to one decimal place before 2008, and thereafter to two decimal places, which may have influenced our ability to detect some temporal changes. The high variability is not surprising and previous analysis of a council data found no observable trends over time (Cavanagh 2014). There have been few other analyses of Cd trends over time, with the exception of McDowell (2012), who suggested that Cd concentrations were plateauing at the Winchmore experimental farm using a mass-balance approach. Further analysis using an extended dataset i.e. additional regionals, over longer time periods, may provide a clearer picture of whether Cd is accumulating under different land-uses.

Improving soil management

Our study indicates that some land uses – and therefore some sites – have mean values of Olsen P greater than is desirable from both production and environmental perspectives. Soil phosphorus concentrations above soil guidelines increase the risk to water quality (e.g. Burkitt et al. 2010; Curran-Cournane et al. 2011; Hart & Cornish 2016). Soil nutrient concentrations above guidelines have also been observed elsewhere (e.g. Cotching & Kidd 2010; Curran-Cournane 2015; Drewry et al. 2015; Gourley et al. 2015; Taylor et al. 2017). Improved management of critical source areas and reduction of farm nutrient surpluses often have little additional cost to farmers (Gourley et al. 2015; McDowell et al. 2015). There is therefore a need for national resourcing of soil to improve policies, capability, and competencies for farm and soil extension and adoption (see Collins et al. 2015).

Improving regional and national reporting

Evaluating temporal trends is useful to help assess whether current policies and soil management practices are effective. For example, the National Cadmium Management strategy takes a risk-based approach to ensure that cadmium in rural production poses minimal risks to health, trade, land use flexibility and the environment over the next 100 years. In addition, a Tiered Fertiliser Management System (TFMS) is a central part of the strategy that aims to minimise Cd accumulation in soil by imposing increasingly stringent fertiliser management practices as Cd concentrations increase. This study indicated there is some evidence of potential (e.g. temporal) effects, but the evidence was difficult to detect. It would therefore be beneficial to combine data from other regions if sufficient data exist over a long-term period, given the limitations or variation in a single region's data. Combining Waikato and Auckland data with our dataset, for example, might enable further, more detailed evaluation, particularly of temporal trends across regions.

To improve regional and national reporting, regional authorities aim to improve consistency of soil quality and trace element monitoring in the Environmental Monitoring and Reporting (EMaR) project through the Land Monitoring Forum. The Land Monitoring Forum initiated a national review of soil quality and trace element monitoring between regional authorities (Cavanagh et al. 2017). The methodology and reporting of several indicators, including Olsen P, have been identified as a potential issue where more consistency may be needed (Drewry et al. 2015; Cavanagh et al. 2017; Taylor et al. 2018).

Cavanagh et al. (2017) identified consistent definitions of land use between regions as important for nationally consistent reporting. This study recognised that consistency within sites is important, given that temporary changes in land cover may occur in a farm system. Our current study identified that farm system was useful for our analysis. We recommend that farm system be considered for future analyses and in other regions.

Conclusions

From our analysis in the region over the period 2000–2017 inclusive, we conclude that for soil Olsen P (phosphorus):

- land use effects were dominant over soil order
- predicted mean values for market gardens were markedly greater than other land uses
- predicted mean values of several land uses were greater than guideline values used in regional reporting, and
- predicted mean annual change over time was lowest in indigenous vegetation and greatest in forestry.

For cadmium, we conclude that dairy land use had a greater mean cadmium concentrations than several other land uses. A significant increase in cadmium soil concentration over time was observed only for horticulture. The high variability in results and the low number of sites, may have masked any trends for other land-uses.

Recommendations

We recommend that:

- Olsen P values be reduced to guideline values
- farm system be considered in future analyses for regional and national reporting
- further analyses be undertaken for other indicators, potentially in combination with other regions to evaluate the data further, and
- further analysis on a wider set of data would help to establish the consistency of any temporal trends.

Acknowledgements

Thanks to the farmers for their participation and access to sampling sites, and to staff who assisted with sampling. Thanks to members of the Land Monitoring Forum for initiatives to improve soil quality monitoring.

References

Burkitt, L.L., Dougherty, W.J., Carlson, S.M., Donaghy, D.J. 2010. Effect of variable soil phosphorus on phosphorus concentrations in simulated surface runoff under intensive dairy pastures. *Australian Journal of Soil Research 48*, 231-237.

Cavanagh, J. 2014. Status of cadmium in New Zealand soils. Landcare Research. Lincoln.

Cavanagh, J., Munir, K., McNeill, S., Stevenson, B. 2017. Review of soil quality, including trace elements, State of the Environment monitoring programme. Landcare Research. Lincoln.

Collins, A., Mackay, A., Hill, R., Thomas, S., Dyck, B., Payn, T., Stokes, S. 2015. Phase 3: Looking forward. Future requirements for soil management in New Zealand. National Land Resource Centre, Landcare Research, Palmerston North.

Cotching, W., Kidd, D. 2010. Soil quality evaluation and the interaction with land use and soil order in Tasmania, Australia. *Agriculture Ecosystems and Environment 137*, 358-366.

Curran-Cournane, F. 2015. Soil quality state and trends in New Zealand's largest city after 15 years. *International Journal of Environmental, Ecological, Geological and Geophysical Engineering 9*, 227-234.

Curran-Cournane, F., McDowell, R., Littlejohn, R. and Condron, L. 2011. Effects of cattle, sheep and deer grazing on soil physical quality and losses of phosphorus and suspended sediment losses in surface runoff. *Agriculture, Ecosystems and Environment 140*, 264-272.

Drewry, J., Curran-Cournane, F., Taylor, M., Lynch, B. 2015. Soil quality monitoring across land uses in four regions: implications for reducing nutrient losses and for national reporting. In: Moving farm systems to improved nutrient attenuation. (Eds L.D. Currie and L.L. Burkitt). Occasional Report No. 28. Fertilizer and Lime Research Centre, Massey University. 14 p.

Drewry, J.J., Littlejohn, R.P., Paton, R.J., Singleton, P.L., Monaghan, R.M., Smith, L.C. 2004. Dairy pasture responses to soil physical properties. *Australian Journal of Soil Research 42,* 99-105.

Fernandez, P.L., Alvarez, C.R., Taboada, M.A. 2011. Assessment of topsoil properties in integrated crop–livestock and continuous cropping systems under zero tillage. *Soil Research 49*, 143-151.

Gourley, C.P.J., Aarons, S.R., Hannah, M.C., Awty, I.M., Dougherty, W.J., Burkitt, L.L. 2015. Soil phosphorus, potassium and sulphur excesses, regularities and heterogeneity in grazing-based dairy farms. *Agriculture, Ecosystems and Environment 201*, 70-82.

Hart, M.R., Cornish, P.S. 2016. Soil phosphorus status and environmental risk of phosphorus run-off from pastures in south-eastern New South Wales. *Soil Research 54,* 685-691.

Hawke, M.F., O'Connor, M. B. 1993. Soil pH and nutrient levels at Tikitere agroforestry research area. *New Zealand Journal of Forestry Science 23*: 40-48.

Hewitt, A.E. 2010. New Zealand soil classification. 3rd ed. Lincoln, New Zealand, Manaaki Whenua Press.

Hill, R.B., Sparling, G., Frampton, C., Cuff, J. 2003. National soil quality review and programme design. Technical Paper No. 75. Ministry for the Environment. Wellington.

Hill, R.B., Sparling, G.P. 2009. Soil quality monitoring. Land and soil monitoring: A guide for SoE and regional council reporting. Land Monitoring Forum. pp. 27-86.

Houlbrooke, D. J., Littlejohn, R. P., Morton, J. D., Paton, R. J. 2008. Effect of irrigation and grazing animals on soil quality measurements in the North Otago Rolling Downlands of New Zealand. *Soil Use and Management 24*, 416-423.

Mackay, A., Dominati, E., Taylor, M. D. 2013. Soil quality indicators: the next generation. Report prepared for Land Monitoring Forum of Regional Councils. AgResearch.

McDowell. R.W. 2012. The rate of accumulation of cadmium and uranium in a long-term grazed pasture: implications for soil quality. *New Zealand Journal of Agricultural Research* 55, 133-146.

McDowell, R.W., Dils, R.M., Collins, A.L., Flahive, K.A., Sharpley, A.N., Quinn, J. 2015. A review of the policies and implementation of practices to decrease water quality impairment by phosphorus in New Zealand, the UK, and the US. *Nutrient Cycling in Agroecosystems* 104, 289-305.

McDowell, R.W. Cox, N., Snelder, T.H. 2017. Assessing the yield and load of contaminants with stream order: would policy requiring livestock to be fenced out of high-order streams decrease catchment contaminant loads? *Journal of Environmental Quality 46*, 1038-1047.

R Core Team 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Sparling, G. P., Schipper, L. A., Bettjeman, W., Hill, R. 2004. Soil quality monitoring in New Zealand: practical lessons from a 6-year trial. *Agriculture, Ecosystems and Environment 104*, 523-534.

Taylor, M.D., Cox N, Littler, R., Drewry J.J. 2017. Trends in soil quality monitoring data in the Waikato region 1995-2015. Waikato Regional Council Technical Report No. 2017/26. Waikato Regional Council, Hamilton New Zealand. 74 p.

Taylor, M., Drewry, J., Stevenson, B., Cavanagh, J., Foster, N. 2018. How closely do different Olsen P measures correlate? In: Farm environmental planning – Science, policy and practice. (Eds L. D. Currie and C. L. Christensen). Occasional Report No. 31. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Taylor, M.D., Kim, N.D., Hill, R.B., Chapman, R. 2010. A review of soil quality indicators and five key issues after 12 yr soil quality monitoring in the Waikato region. *Soil Use and Management 26*, 212-224.