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SOIL QUALITY AND TRACE ELEMENTS FOR LAND USES IN THE WELLINGTON REGION AND IMPLICATIONS FOR FARM MANAGEMENT

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Abstract

This paper reports on soil quality (soil health) indicators and trace elements undertaken for the State of the Environment monitoring programme in the Wellington region of New Zealand. Land uses monitored included drystock, dairy, market gardening (vegetables), cropping (arable), horticulture (orchards, viticulture), exotic forest and indigenous vegetation. Soil measurements monitored were pH, anaerobically mineralised nitrogen, total nitrogen, Olsen P, organic carbon, hot water extractable carbon, bulk density, macroporosity, arsenic, cadmium, copper, zinc and total fluoride. Hot water extractable carbon and total fluoride had not been previously reported for this region. Sites with soil quality indicators outside targets may have increased risk of reducing environmental condition, such as through nutrient loss from land to water, or may have reduced farm production.

Results show that in the Wellington region, soil pH, anaerobically mineralised nitrogen, and total nitrogen are mostly within targets, but macroporosity is low for some land uses, indicating soil compaction. Organic carbon and hot water carbon values are mostly within targets, but market gardens and cropping land uses show some carbon loss. Several methods for reporting Olsen P are reported. Many land uses have some Olsen P (phosphorus) values greater than is desirable for production or environmental outcomes, with potentially increased risk to water quality. All sites have arsenic and zinc levels within guidelines, but copper levels are elevated for several sites.

Greater Wellington Regional Council has programmes to help improve farm, catchment and water quality management by working in partnership with landowners to identify, develop and implement good management practice on farms in priority catchments. Programmes include assisting farmers with riparian planting and hill country erosion control using farm and environment plans. Through Greater Wellington's farm and environment plan programme we recognise the need to move away from a method of engagement that is solely focused on mitigations, to one that works alongside farmers to provide information to enable them to make informed management decisions when identifying actions to improve soil health.

Introduction

Greater Wellington Regional Council and other regional authorities monitor soil quality (soil health) for State of the Environment (SoE) monitoring. To improve reporting, regional authorities via the Land Monitoring Forum are improving nationally consistent soil quality and trace element monitoring in the Environmental Monitoring and Reporting (EMaR) project. Soil quality issues vary with land use and management but commonly include low levels of organic carbon, above optimum nutrients, and soil compaction (Curran-Cournane

2015, Drewry et al. 2015; McDowell et al. 2015; Taylor et al. 2016). SoE monitoring commonly includes diffuse source trace element contaminants that may accumulate in soil. Sources include current or historic use of pesticide sprays, animal remedies, veterinary medicines (arsenic (As), copper (Cu), lead (Pb), zinc (Zn)), or phosphorus fertiliser application (cadmium (Cd), fluoride (F)). Where application of these have occurred, some sites have accumulated trace element levels above recommended soil guidelines (e.g. As, Cd, Cu; Taylor et al. 2010).

To improve water quality and reduce erosion, the Land Management department of Greater Wellington has a programme for assisting farmers with riparian planting, hill country erosion control, and improved farm and nutrient management via farm and environment plans (FEPs). Recently the council has initiated more resourcing to improve soil and catchment management. This paper reports on soil quality and trace element indicators from recent monitoring, and discusses opportunities for improved management and recent initiatives to improve catchment water quality.

Overview of soil quality indicators

Soil chemical and biological indicators include pH, organic carbon (OC), anaerobically mineralised N (AMN), total nitrogen (TN), and Olsen P. AMN is an indicator of how much organic nitrogen can become available to plants from decomposition of organic matter, and is correlated with microbial biomass. Olsen P is an indicator of plant-available P. Regular trace element measurements include As, Cd, Cr, Cu, Pb, Ni and Zn, and more recently F. Hot water extractable carbon (HWC) is an integrated measure of soil biochemical quality as it is correlated with microbial biomass-C, mineralisable N and micro-aggregation of soils (Ghani et al. 2003). The Land Monitoring Forum is trialling HWC as an alternative to AMN. Soil physical properties are macroporosity and bulk density. Macroporosity is the percentage of large pores (>30 microns, measured at -10 kPa) responsible for soil drainage and aeration. Macroporosity is a sensitive indicator of compaction (Drewry et al. 2008).

Methods

Although the soil quality monitoring started in 2000, only some measurements were analysed until 2011. Therefore the monitoring period in this study was 2011 to 2015 inclusive (5 years), and includes sites on six soil orders and various land uses. Predominant soil orders were (site numbers shown) Pallic (29), Recent (28), Brown (26), Gley (12), with Melanic (2) and Allophanic (1) Soils.

Measurements – soil chemical, biological, physical and trace elements

Details of field methods are reported in the Land Monitoring Forum report (Hill and Sparling 2009). Briefly, at each site a 50 m transect was used to take 10 cm depth soil cores, taken approximately every 2 m. Individual cores were bulked and mixed to obtain a representative sample. Soil chemical measurements were analysed by Landcare Research. Olsen P is measured on a gravimetric (weight) basis and therefore avoids the confounding influence of soil field bulk density. In New Zealand, several large commercial laboratories measure soil by volume of sieved and dried sample prior to the chemical extraction. Fertiliser industry guidelines for Olsen P also use that volumetric method. Further details are in Drewry et al. (2013; 2015). In addition, a sub-sample was also analysed for Olsen P directly from Hill Laboratories (volumetric basis) for some land uses. Samples for trace elements were sampled as above (Kim and Taylor 2009). Total recoverable trace elements were analysed by Hill Laboratories in Hamilton. Total fluoride was measured by Hill Laboratories using alkaline fusion. HWC was measured by AgResearch (Ghani et al. 2003).

Three undisturbed (intact) soil samples were obtained from each site (Hill and Sparling 2009). The intact cores were collected along the transect by pressing steel liners (10 cm in diameter and 7.5 cm in depth) into the soil. From these intact cores, a 3 cm subsample ring was used in the Landcare Research laboratory in Hamilton to determine bulk density and macroporosity (percentage of pores > 30 microns, measured at -10 kPa matric potential).

Guidelines and targets

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 indicators is reporting 'by exception' (Hill and Sparling 2009). Updated Olsen P and other guidelines were reported in Mackay et al. (2013). Refer to Table 1. Some guidelines do not apply to indigenous vegetation sites or some land uses.

Table 1: Target or guidelines used for regional authority soil quality monitoring.

Indicator	Unit	Land use				
		Cropping	Pasture	Forestry	Horticulture	Market garden
Bulk density	(Mg/m^3)	Pallic, Recent soils (0.4-1.4), other soils (0.7-1.4)				
Macroporosity	(% v/v)	10-30	10-30	10-30	10-30	10-30
pH [A]		5-7.6	5-6.6	3.5-7.6	5-7.6	5-7.6
AMN	(mg/kg)	>20	>50	>20	>20	>20 [B]
TN	(%)	excl	0.25-0.7	0.1-0.7	excl	excl
OC	(%)	Pallic, Recent soils (2-12), other soils (2.5-12)				
HWC	(mg/kg)	>1400	>1400	>1400	>1400	>1400
Olsen P [C]		20-40	20-40	5-30	20-40	20-40 [B]
Olsen P [C] hill country			15-20			

[A] pH for non organic soils. Macroporosity at -10 kPa. Excl, targets are dependent on crop type or are not well defined. [B] included as cropping. HWC is provisional recommended by Taylor (pers comm). [C] mg/kg or mg/L, sedimentary soil Olsen P value shown.

Trace elements were compared with guidelines adapted from NZWWA (2003), as used by the Land Monitoring Forum. See later section for values. Cadmium was compared with the Tiered Fertiliser Management System (TFMS; Cavanagh 2014). Draft soil guideline values for the protection of ecological receptors have recently been developed to protect soil and terrestrial biota (Eco-SGVs; Cavanagh and Munir 2016). Eco-SGVs provide a means to assess potential environmental impact, or provide a benchmark for soil quality. Further research and consultation of draft values may be required. For fluoride, a value of 500 mg/kg was used for comparison. This value was suggested by Loganathan et al. (2006) and Jha et al. (2008) to avoid animal health problems, although the value can vary with stock type and circumstances (Loganathan et al. 2006; Kim et al. 2016).

Statistical analysis

All graphical and statistical analyses were carried out using the statistical package 'R' version 3.3.1 (R Core Team 2016). For boxplots, median is shown, and the boxes represent the inter-quartile range, IQR (25th and 75th percentile), and whiskers represent 1.5xIQR. Outliers are illustrated with circles. Given the methodology differences for Olsen P described above and in Drewry et al. (2013; 2015), three analyses are reported. Analysis (A) *reported as gravimetric results*, for the Landcare Research gravimetric data (mg/kg). Analysis (B) *reported as calculated volumetric results*, had gravimetric laboratory data converted to volumetric equivalent units by multiplying by undisturbed field bulk density. In addition, the volumetric Olsen P values direct from *Hill Laboratories (volumetric)* is indicated as analysis

(C). The land use classification used is presented in Table 2. Sites that had major changes in land use were excluded to maintain consistent land use.

Table 2: Land use classification.

Land use	Number of sites, n	Notes
Cropping	7	Extensive arable cropping
Dairy	16	Milking platform
Drystock	32	Sheep, beef, deer, dairy runoff
Forestry	7	Exotic forestry (pine)
Horticulture	11	Orchards, vineyards
Market gardens	9	Intensive vegetables
Indigenous	16	Native bush or indigenous vegetation

Results

Percentage of sites outside the soil quality target range

The percentage of sites outside the target/guideline ranges described earlier (i.e. below lower target and/or above upper target) per land use is presented in Table 3. AMN and pH generally had a low percentage of sites outside guidelines. For OC and bulk density, most land uses were within guidelines with the exception of market garden sites. Several land uses had a large percentage of sites outside target ranges for macroporosity, HWC and Olsen P.

Table 3: Percentage of sites within each land use that are outside target ranges.

Indicator	Unit	Land use					
		Cropping	Dairy	Drystock	Forestry	Horticulture	Market garden
Bulk density	(Mg/m^3)	0	6	0	0	0	33
Macroporosity	(% v/v)	57	81	31	29	45	33
pH		0	6	3	0	0	0
AMN	(mg/kg)	0	0	0	0	0	11
TN	(%)	excl	25	19	14	excl	excl
OC	(%)	0	0	0	0	0	56
HWC	(mg/kg)	86	0	0	ND	ND	100
Olsen P [A]	(mg/kg)	43	81	72	43	82	100
Olsen P [B] calc	(mg/L)	71	88	63	57	73	89
Olsen P [C] Hill Lab	(mg/L)	43	56	56	ND	ND	78

[A] Method A, mg/kg. [B] Method B, mg/L (calculated using bulk density). [C] Method C, mg/L (Hill Laboratories). Macroporosity at -10 kPa. Excl, targets are dependent on crop type or are not well defined. ND not determined.

Macroporosity and bulk density

Macroporosity and bulk density for each land use are presented in Figure 1. Median macroporosity was greatest in market garden sites (16.8%) with lowest median value for dairy sites (6.5%). The percentage of sites that did not meet macroporosity target values was greatest in dairy sites (81%), followed by cropping sites (57%), and was lowest in drystock sites (31%; Table 3). Market garden sites had the greatest median bulk density (1.35 Mg/m^3) and percentage of sites that did not meet targets (33%).

Carbon and nitrogen indicators

OC and HWC by land use are presented in Figure 2. Median OC was greatest in indigenous vegetation sites (6.8%), low in cropping sites (2.8%) and lowest in market garden sites (2%). All land use sites met OC targets except for 56% of market garden sites (Table 3). All dairy and drystock sites were within the HWC provisional target. No market garden sites (median

639 mg/kg) met the provisional HWC target. For HWC, 86% of cropping sites did not meet the provisional target. The percentage of sites not meeting TN target values are presented in Table 3. All sites were within the AMN guideline except some market garden sites.

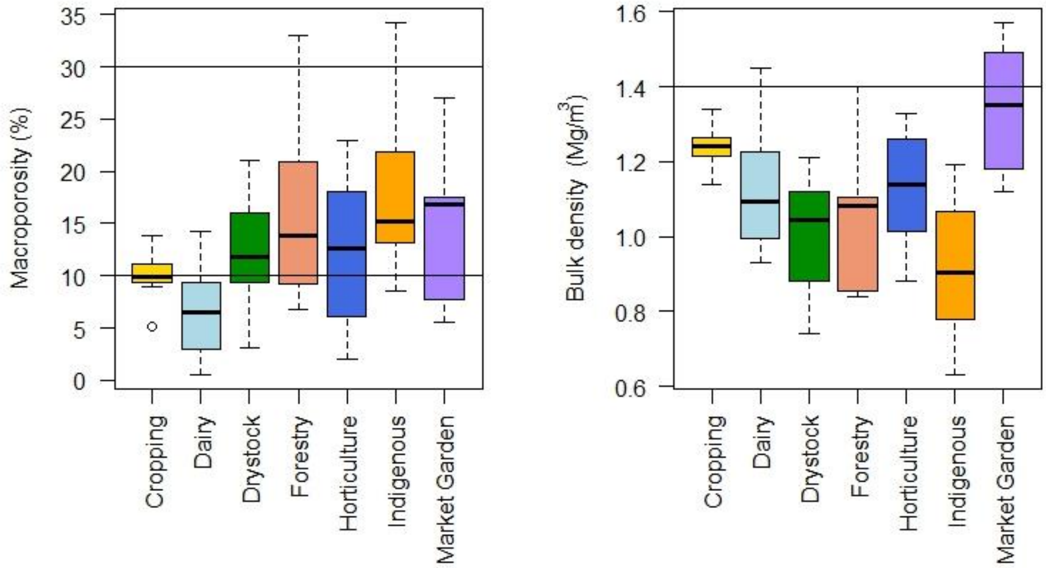

Figure 1: Macroporosity (% v/v) and bulk density (Mg/m^3) grouped by land use. Thick black line is median (50th percentile). Box represents the 25th to 75th percentile. See method for explanation. Guidelines from Mackay et al. (2013) are shown.

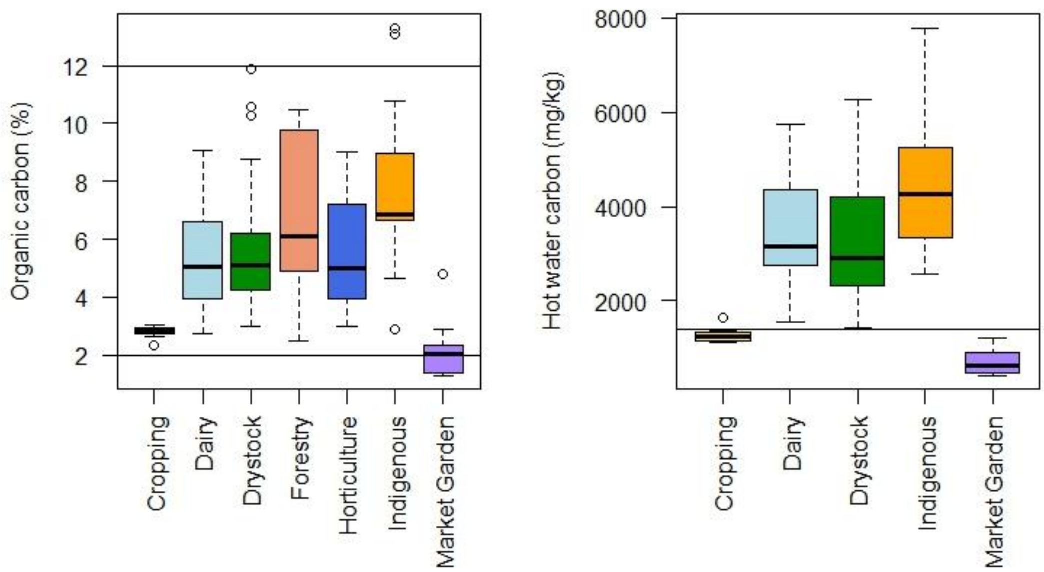

Figure 2: Organic carbon (%) and hot water carbon (mg/kg) grouped by land use. OC guidelines shown are for Pallic and Recent soils.

Olsen P

Analysis (A) gravimetric results (mg/kg)

Olsen P values reported in gravimetric units are presented in Figure 3A. Median Olsen P was greatest in the market gardening sites (159 mg/kg), with all sites above guidelines. Median Olsen P values were horticulture (79 mg/kg), dairy (67 mg/kg), drystock (41 mg/kg), cropping (36 mg/kg), forestry (32 mg/kg) and indigenous (17 mg/kg). For Olsen P (gravimetric), 82% of horticulture sites, 81% of dairy, 72% of drystock sites and 43% of cropping and forestry sites did not meet guideline values (Table 3).

Analysis (B) calculated volumetric results (mg/L)

Olsen P values calculated in volumetric units using undisturbed bulk density (Figure 3B) showed similar general results to the gravimetric values, including broadly similar results for the percentage of sites not meeting guideline values. For Olsen P (calculated), 88-89% of dairy and market gardens did not meet guideline values (Table 3). Median Olsen P (calculated) were cropping (47 mg/L), dairy (75 mg/L), drystock (38 mg/L), indigenous (15 mg/L), and market gardens (200 mg/L).

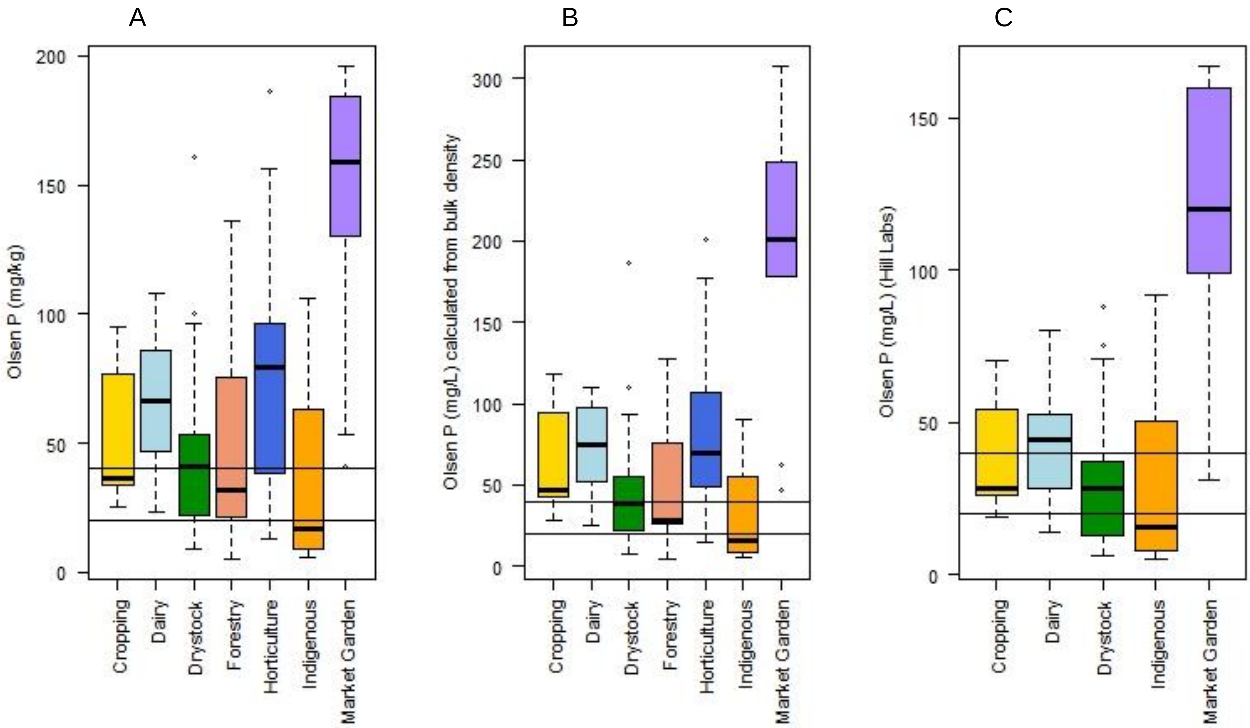

Figure 3: Olsen P grouped by land use for the three methods. (A) Analysis A gravimetric (mg/kg); (B) Analysis B calculated volumetric from bulk density (mg/L); and (C) Analysis C direct volumetric from Hill Laboratories (mg/L). Selected guidelines from Mackay et al. (2013) are shown to assist the reader in interpretation and do not apply to all land uses – see Table 1 for details.

Analysis (C) direct volumetric results (mg/L)

The Olsen P values direct from Hill Laboratories (Figure 3C) also showed broadly similar grouping of results by land use (Figure 3C; Table 3). Median Olsen P values on direct volumetric basis were cropping (28 mg/L), dairy (45 mg/L), drystock (29 mg/L), indigenous (16 mg/L), and market gardens (120 mg/L).

Trace elements As, Cd, Cu, F and Zn

Soil As concentrations were all below the guideline value of 20 mg/kg, which is also the draft eco-SGV for agricultural land. Median As values for all land uses ranged from 3-4 mg/kg. The majority of sites had soil Cd concentrations that were below the Tier 0 TFMS trigger value of 0.6 mg/kg (Figure 4). All sites were below the Cd Tier 1 trigger value of 1.0 mg/kg, and the draft eco-SGV of 3.1 mg/kg. Median Cd values were cropping (0.19 mg/kg), dairy

(0.33 mg/kg), drystock (0.23 mg/kg), forestry (0.12 mg/kg), horticulture (0.29 mg/kg), indigenous (0.11 mg/kg) and market gardens (0.20 mg/kg).

Ninety-eight percent of sites were below the Cu guideline value of 100 mg/kg. Two (18%) horticultural sites were above this guideline (Table 4; Figure 4). Only one horticultural site on Recent Soil was above the draft Cu eco-SGVs for agricultural land, namely 130 mg/kg for sensitive soil (Recent Soil) and 150 mg/kg for typical soil (Brown Soil). Eleven percent of sites had Cu values ≤ 5 mg/kg, a suggested guideline value for deficiency (Alloway 2008).

There are very few studies on the toxicity of soil fluoride (Cavanagh and Munir 2016). The 500 mg/kg value described earlier is not a guideline, so caution is needed in interpretation. Further research is likely to be required to derive risk-based guidelines for some soil parent materials and land uses. Median fluoride values for land uses ranged from 255-430 mg/kg. Six percent of sites exceeded 500 mg/kg for soil fluoride (Figure 5). Soil Zn concentrations were all below the guideline value of 300 mg/kg (Figure 5). Median Zn values for land use ranged from 45-89 mg/kg. There were 98% of sites below the draft Zn eco-SGVs for agricultural land, namely 130 mg/kg for sensitive soil (Recent Soil) and 190 mg/kg for typical soil (Brown Soil).

Table 4: Percentage of sites per each land use exceeding guideline or trigger value.

Indicator	Guideline	Land use					
		Cropping	Dairy	Drystock	Forestry	Horticulture	Market garden
As [A]	20 mg/kg	0	0	0	0	0	0
Cd [B]	0.6 mg/kg	0	12	3	14	9	0
Cd [C]	1.0 mg/kg	0	0	0	0	0	0
Cu [A]	100 mg/kg	0	0	0	0	18	0
Zn [A]	300 mg/kg	0	0	0	0	0	0

[A] NZWWA (2003). [B] Tier 0 TFMS trigger value of 0.6 mg/kg. [C] Tier 1 TFMS trigger value of 1.0 mg/kg.

Discussion and implications for farm management

Soil quality indicators

Soil compaction, as indicated by low macroporosity values, was common on dairy sites (81%), and to a lesser extent on cropping sites (57%). Approximately one-third of drystock sites were considered compact. Soil compaction can result in reduced air and water permeability of soil, and increased runoff that can transport nutrients, pathogens and other contaminants to waterways. It is generally considered that pasture and crop yields are reduced when macroporosity is below approximately 10%, although optimum macroporosity values for maximum pasture and crop yield do vary (Drewry et al. 2008; Reynolds et al. 2008). Pasture and crop yield gains could be made on sites with very low values.

Improving soil physical condition where it is compacted, and reducing nutrient (P) levels where they are high, is a win-win for farmers and environmental outcomes. When soil is compact, generally increased runoff can occur, due to reduced soil infiltration. Surface runoff can carry contaminants to waterways. Therefore, if compact pastoral soil, critical source areas, or other sites coincide with elevated soil P concentrations, those sites could be at greater risk to contribute nutrients to waterways (Gourley et al. 2015; Lucci et al. 2009; McDowell et al. 2015; Taylor et al. 2016).

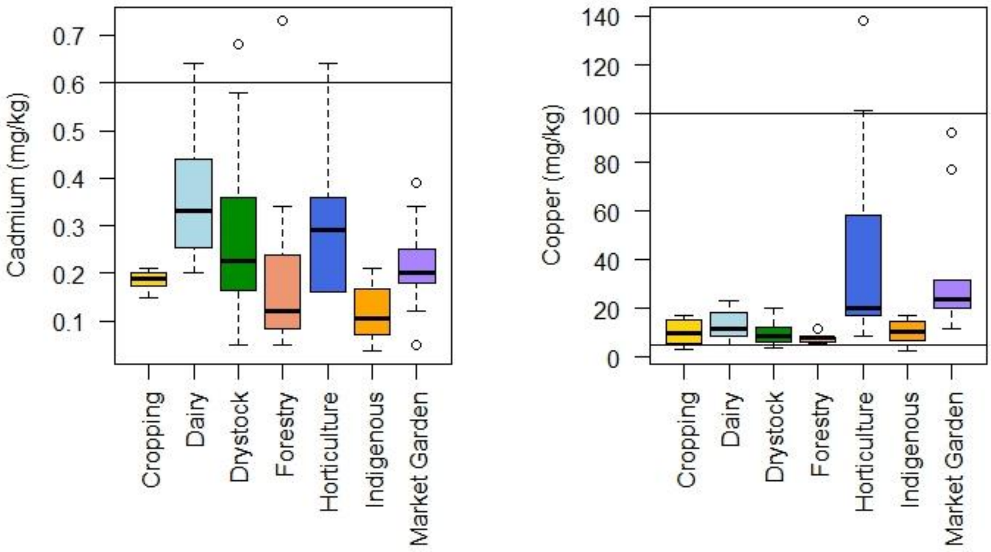

Figure 4 Cadmium (mg/kg) and copper (mg/kg) grouped by land use. Cadmium TFMS Tier 0 trigger (0.6 mg/kg) and suggested value for copper deficiency (≤ 5 mg/kg) shown.

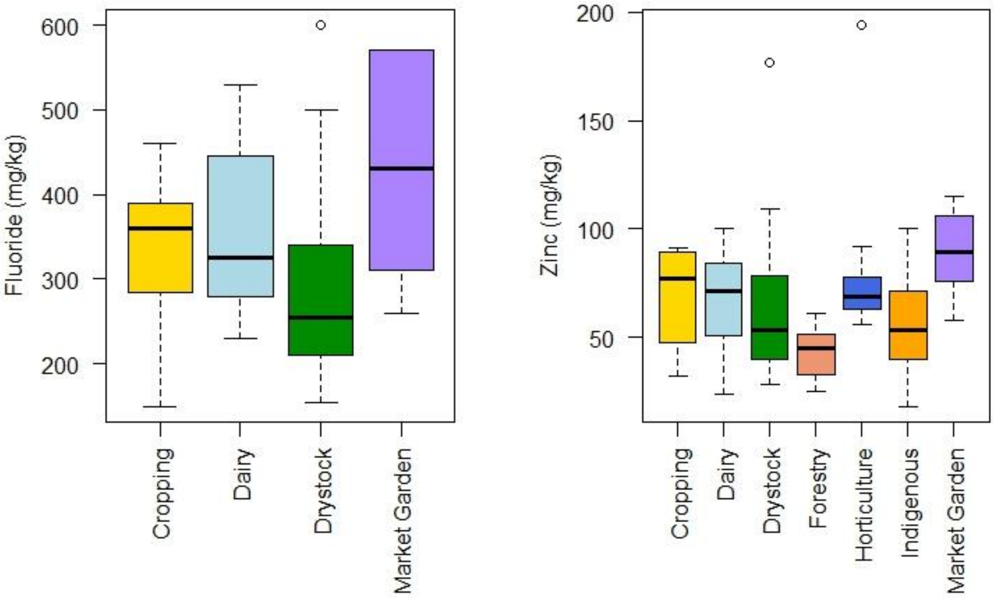

Figure 5: Fluoride (mg/kg) and zinc (mg/kg) grouped by land use. Guideline for zinc not shown as value is 300 mg/kg.

Regardless of the assessment indicator (methods A, B or C) for Olsen P, this study shows some land uses and sites have much greater Olsen P values than is desirable, even from production or agronomic perspectives. Reducing P levels to environmental or agronomic targets would result in a win-win reducing in P loads from some sites, and reducing input costs for farmers. Soil P, K, and S concentrations above agronomic targets, and nutrient accumulation were also commonly observed in Australian dairy systems by Gourley et al. (2015). Vegetable production has greater agronomic optimum values than pasture. Clarke et al. (1986) recommended optimum Olsen P values of 46-75 mg/L for brassicas, spinach and silverbeet. Targets in Mackay et al. (2013) also account for environmental effects. For farm management and extension activities, reducing Olsen P to agronomic targets is highly costeffective to reduce phosphorus loads to water, while improved management of critical source areas and reducing farm nutrient surpluses often have little additional cost to farmers (Gourley et al. 2015; McDowell et al. 2015).

Some indigenous sites had higher than expected Olsen P values. Some sites adjacent to pasture may have been influenced by fertiliser drift. Stevenson (2004) reported greater soil Olsen P values in forest fragments than in larger forests. Different nutrient cycling processes and stock access may be factors involved, but further research is needed to determine this. In a study of similar land use soil monitoring as the current study, Hermans et al. (2017) noted that bacterial community composition was influenced by Olsen P and soil quality, with positive and negative relationships between Olsen P on the abundance of some taxa.

Market gardens have low OC, an indicator of soil organic matter. HWC was lower than desirable in cropping and market gardens, likely as a result of continuous cultivation. HWC appears a more sensitive indicator than OC and AMN as it measures a readily bioavailable fraction of soil organic matter. Soils that have lost OC can have reduced stability, aggregation, porosity, infiltration, drainage, aeration, nutrient retention and mineralisation, and microbial activity, which makes soil vulnerable to compaction, slaking, capping, nutrient and trace element leaching, erosion and runoff losses (Blanco-Canqui and Schlegel 2012; Dick and Gregorich 2004). Scarce organic matter can result in less diversity in soil biota (Hermans et al. 2017).

Trace elements
Trace elements may be present due to past pesticide applications (e.g. lead arsenate was formerly used in orchards) or from on-going use (e.g., copper fungicides are still widely used to protect pipfruit from black spot fungus). Copper is also found in manures, such as piggery and poultry waste, and treated timber (Taylor 2016). However, soil Cu concentrations were well below guidelines on all land uses except horticulture, probably reflecting use of copper fungicides. Too much copper can be toxic to some plants, soil microorganisms and invertebrates (Alloway 2008; Cavanagh and Munir 2016).

Most sites were below the Cd Tier 0 TFMS trigger value of 0.6 mg/kg. That TFMS level indicates concentrations are within the range of background values found in New Zealand soils (Abraham et al. 2016). All sites were below the TFMS Tier 1 trigger value of 1.0 mg/kg. At Tier 1 (0.6 to <1.0 mg/kg) some fertiliser and management changes may be needed to minimise further accumulation (Abraham et al. 2016). Note that as part of the TFMS Cavanagh (2014) recommends that before considering management actions on a farm, sampling from at least six paddocks within a farm land management unit should be undertaken to provide a representative concentration for the farm, hence our study provides only an initial indication.

Phosphate fertilisers are the main source of fluoride to New Zealand soils, where it accumulates (Taylor 2016; Kim et al. 2016). Draft eco-SGVs were considered by Cavanagh and Munir (2016) as provisional, so were not used for comparison because of lack of toxicity data, and only volcanic soils were available for assessment. The 500 mg/kg value to avoid possible animal health problems was exceeded on a small percentage of sites, but some caution is needed in interpretation (Kim et al. 2016). Further research is needed to determine guideline values.

Farm and environmental plans

The Land Management department's farm and environment plan (FEP) programme works in partnership with landowners to identify, develop and implement good management practice on farms in priority catchments. Priority catchments with degraded water quality, and the need for implementing improved practice, have been identified as part of the proposed Natural Resource Plan. The programme provides financial incentives for on-ground works, including riparian fencing and planting to improve water quality and environmental outcomes. Other mitigations such as catch crops and strategic grazing of critical source areas to improve soil and water quality are being promoted. These mitigations require practice change and funding so will need to be channelled into extension as opposed to financial incentives only.

Council sustainable agriculture advisors observe that that many farmers in the region undertake some kind of soil testing for assessing fertiliser requirements, but with tests often infrequent or taken at a broad scale. In Australia and the United States, Lobry de Bruyn and Andrews (2016) showed that although common practice is for decisions on fertiliser application, they indicated that many farmers report the use of observations in lieu of laboratory testing. That study highlighted the need for soil information to include observational indicators so a mix of traditional extension strategies can be made with digital technologies. Through Greater Wellington's FEP programme we are recognising the need to move away from a method of engagement with farmers that is solely focused on mitigations, to one that works alongside farmers to provide information to enable them to make informed management decisions when identifying actions to improve soil health. Fundamental to soil security is the need for farmers to better understand soils, apply the appropriate management practices, and monitor soil quality or fertility over time. Nationally too, extension activities for raising awareness of soil quality and management should be prioritised. Collins et al. (2015) highlighted the needs for national resources and leadership of soil to improve policies, and improve soil related capability and competencies for extension and adoption.

Conclusions

From this study we conclude that for soils in the Wellington region:

- That pH, AMN and TN are mostly within targets, but macroporosity is low for some land uses, indicating compaction;
- Organic carbon and hot water carbon values are mostly within targets, except HWC for market garden and cropping sites, and OC for some market gardens, indicating loss of organic carbon in some land uses;
- Regardless of assessment method, many land uses particularly market gardens, have some phosphorus values greater than is desirable, with increased risk to water quality; and
- All sites have arsenic and zinc levels well within guidelines, and below the cadmium TFMS Tier 1 trigger value, but copper levels are elevated for several sites.

In relation to soil quality and regional catchment management we recommend that resourcing is prioritised for extension to work with and provide information to assist farmers to make informed soil management decisions.

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References

Abraham, E., Cavanagh, J., Wood, P., Pearson, A., Mladenov, P. 2016. Cadmium in New Zealand's agriculture and food systems. In: Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R. Singh). Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University. 13 p.

Alloway, B.J. 2008. Copper and zinc in soils: too little or too much? In: (Ed N. Kim) New Zealand Trace Elements Group conference. Hamilton. 10 p.

Blanco-Canqui, H., Schlegel, A.J. 2012. Implications of inorganic fertilization of irrigated corn on soil properties: lessons learned after 50 years. *Journal of Environmental Quality 42,* 861-871.

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

Cavanagh, J., Munir, K. 2016. Development of soil guideline values for the protection of ecological receptors (Eco-SGVs): Technical document. Prepared for: Regional Waste and Contaminated Land Forum, Land Monitoring Forum and Land Managers Group. Envirolink Tools Grant: C09X1402. Landcare Research. Lincoln.

Clarke, C.J., Smith, G.S., Prasad, M., Cornforth, I.S. 1986. Fertiliser recommendations for horticultural crops. Ministry of Agriculture and Fisheries, Wellington.

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.

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.

Dick, W., Gregorich, E. 2004. Developing and maintaining soil organic matter levels. In: Managing soil quality: challenges in modern agriculture. (Eds S. Schjonning, S. Elmholt, B. Christensen). Wallingford, UK, CABI Publishing. Pp 103-120

Drewry, J.J, Cameron, K.C., Buchan, G.D. 2008. Pasture yields and soil physical property responses to soil compaction from treading and grazing - a review. *Australian Journal of Soil Research 46,* 237-256.

Drewry, J., Taylor, M., Curran-Cournane, F., Gray, C., McDowell, R. 2013. Olsen P methods and soil quality monitoring: are we comparing apples with apples? In: Accurate and efficient use of nutrients on farms. (Eds L.D. Currie and C.L. Christensen). Occasional Report No. 26. Fertilizer and Lime Research Centre, Fertilizer and Lime Research Centre, Massey University. 12 p.

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.

Ghani, A, Dexter, M., Perrott, K.W. 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biology and Biochemistry 35,* 1231-1243.

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.

Hermans, S.M., Buckley, H.L., Case, B.S., Curran-Cournane, F., Taylor, M., Lear, G. 2017. Bacteria as emerging indicators of soil condition. *Applied and Environmental Microbiology 83*, e02826-16. doi.org/10.1128/AEM.02826-16.

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.

Jha, S., Nayak, A., Sharma, Y. 2008. Response of spinach (*Spinacea oleracea*) to the added fluoride in an alkaline soil. *Food and Chemical Toxicology 46*, 2968-2971.

Kim, N.D., Taylor, M.D. 2009. Trace element monitoring. Land and soil monitoring: A guide for SoE and regional council reporting. Land Monitoring Forum. pp. 117-165.

Kim, N.D., Taylor, M., Drewry, J. 2016. Anthropogenic fluorine accumulation in the Waikato and Bay of Plenty regions of New Zealand: comparison of field-data with projections. *Environmental Earth Sciences 75*, 147; doi 10.1007/s12665-015-4897-2

Lobry de Bruyn, L., Andrews, S. 2016. Are Australian and United States farmers using soil information for soil health management? *Sustainability 8*, 304; doi:10.3390/su8040304

Loganathan, P., Gray, C.W., Hedley, M.J., Roberts, A.H.C. 2006. Total and soluble fluorine concentrations in relation to properties of soils in New Zealand. *European Journal of Soil Science 57*, 411-421.

Lucci, G.M., McDowell, R.W., Condron, L.M. 2010. Potential phosphorus and sediment loads from sources within a dairy farmed catchment. *Soil Use and Management 26*, 44-52.

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., 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.

NZWWA. 2003. Guidelines for the safe application of biosolids to land in New Zealand. New Zealand Water and Wastes Association, Wellington.

R Core Team 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reynolds, W.D., Drury, C.F., Yang, X.M., Tan, C.S. 2008. Optimal soil physical quality inferred through structural regression and parameter interactions. *Geoderma 146*, 466-474.

Stevenson, B.A. 2004. Changes in phosphorus availability and nutrient status of indigenous forest fragments in pastoral New Zealand hill country. *Plant and Soil 262*, 317-325.

Taylor, M.D. 2016. The fate and impact of fertiliser derived contaminants in New Zealand soils – development of a priority assessment model. Fakultät Architektur, Bauingenieurwesen und Umweltwissenschaften der Technischen Universität Carolo-Wilhelmina zu Braunschweig zur Erlangung des Grades eines Doktors der Naturwissenschaften (Dr. rer. nat.) genehmigte dissertation.

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.

Taylor, M.D., Drewry, J.J., Curran-Cournane, F., Pearson, L., McDowell, R.W., Lynch, B. 2016. Soil quality targets for Olsen P for the protection of environmental values. In: Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R. Singh). Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University. 12 p.