SPATIAL DISTRIBUTION OF SOIL CADMIUM IN A LONG-TERM WAIKATO DAIRY FARM

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Abstract

Cadmium (Cd) accumulation in New Zealand agricultural soils has been linked primarily to phosphorus (P)-fertiliser application history. Land that has traditionally been intensively farmed with a rich history of P-fertiliser inputs is therefore likely to have the most enriched soil Cd concentrations.

As a consequence, long-term dairy farms represent a land use likely to be most impacted by the introduction of the Tiered Fertiliser Management System (TFMS). However, there is little information available regarding spatial variability of soil Cd within these farm systems. Without this knowledge, it is difficult to implement a soil sampling strategy with confidence that it will reliably represent a properties true soil Cd ‘tier-status’ within the TFMS. Furthermore, knowledge of soil Cd spatial variability is likely to be important to farmers and advisors since this may influence management and/or mitigation options and costs.

Soil Cd spatial distribution has been mapped for a long-term dairy farm in the Waikato region with contrasting Allophanic and Gley soils. This spatial variability information will provide the platform for further research including assessment of Cd accumulation in selected animal forage species under different soil, soil Cd concentration and environmental conditions.

Introduction

Soil Cd accumulation in New Zealand agricultural soils has been shown to be strongly related to P-fertiliser application history (Roberts et al., 1994). To manage Cd accumulation in agricultural soils, the fertiliser industry has self-regulated maximum permissible Cd concentrations in its fertilisers, set at 280 mg Cd kg^{-1} P since 1997. Further to this, in 2011 the TFMS was introduced, providing a national framework by which landowners can manage soil Cd accumulation in agricultural land. The TFMS is based around five Cd management tiers separated by four soil Cd concentration ‘trigger values’ (MAF, 2011). The principle of the TFMS is that as soil Cd concentration increases, tighter restrictions on P-fertiliser management apply, to the point where at 1.8 mg Cd kg^{-1} soil, no further soil Cd accumulation is permitted without a site-specific risk investigation being carried out.

In addition, a new set of soil contaminant standards have been developed to manage risk of human exposure to Cd as part of the National Environmental Standard for Assessing and Managing Contaminants in Soil to Protect Human Health (NES). Agricultural land is currently exempt from the NES; however, under the NES the conversion of agricultural to rural-residential or residential land use triggers a requirement for contaminated land assessment (MfE, 2011). At its most stringent (conversion to rural residential land use) the default soil Cd standard within the NES is just 0.8 mg kg^{-1}. This soil Cd concentration is within the range reported for New Zealand agricultural soils (Roberts et al., 1994; Taylor et al., 2007). In some circumstances, remediation of agricultural land would therefore be required before conversion to rural-residential land use is allowed.

The TFMS and NES therefore has potential to introduce new management restrictions on landowners based on soil Cd concentration values for the block or property against the 'trigger' or 'contaminant standard' values within the TFMS or NES, respectively. In particular, this is the case where historically intensive land use has driven high P-fertiliser inputs for long periods, resulting in greater soil Cd enrichment. Previous research has shown long term dairy and horticultural land use on allophanic, pumice and organic soil orders (Roberts et al., 1994; Taylor et al., 2007) are likely to have the most enriched soil Cd concentrations.

For landowners, farm advisors and fertiliser company representatives, this this has created renewed interest in the spatial variability of soil Cd. Uncertainty exists as to what degree of soil Cd variation exists within a farm landscape. This may influence how a property should be sampled to obtain a representative soil Cd concentration value for the block or property. Furthermore, landowners wishing to implement least cost soil Cd management or mitigation strategies have little information to base decisions upon, in terms of what a soil Cd value means in terms of its spatial continuity.

Research has been initiated within a wider PhD research project that seeks to improve our knowledge of soil Cd variability within two long-term dairy farms with differing soil types and management history. This paper provides an overview of data from one of these farms, a Waikato dairy farm that has been under dairying land use since the 1950's.

Property description

The property has a total effective area of 82 ha, consisting of predominantly rolling contour. The predominant soil types on the property are the well-drained Kereone fine sandy loam (Allophanic soil order) and poorly-drained Topehaehae sandy clay loam (Gley soil order), which account for approximately 75% and 15% of the total effective area, respectively.

The property has traditionally had a rich history of P-fertiliser input, predominantly applied as superphosphate. Records from 1995 to 2001 indicate an average annual application rate of 55 kg P/ha, although no records exist prior to this time. Over the period 2001-2013 this reduced to an average annual application rate of approximately 21 kg P/ha. This reduction in P-fertiliser application rate reflects the higher than optimum P-fertility that existed in the early 2000's (average Olsen-P approximately 55 mg/L) and the consequent opportunity to reduce P-fertiliser inputs with little risk to production.

The property has had little cultivation history, with very little cropping or pasture renewal undertaken. Prior to 2001, effluent was applied direct from a collection sump at the dairy shed to only two paddocks (paddocks 3 and 4, Figure 1.a). Since 2001, a holding pond has been in use, with liquid effluent applied to paddocks 3-6, 12-13 and 15-19. No differentiation in fertiliser management has occurred for parts of the farm receiving liquid effluent. Sludge from the holding pond has been applied annually to paddock 14, which has not had any other P-fertiliser input since 2001. Aside from this, P-fertiliser input has been relatively uniform across the rest of the property, regardless of landform, land use management, or soil type.

Inter-paddock soil Cd variability

A detailed soil map (Figure 1.b) and digital elevation model (Figure 1.c) were generated for the property with assistance from Massey University staff. Each paddock within the property was individually analysed for soil total Cd concentration, at 0-75 mm and 75-150 mm depth. In addition, other soil fertility measures including soil total-P were assessed within the 0-75 mm soil depth range.

Where practical, care was taken when sampling to place transects in areas where there was minimal soil type variation, and where the soil type / landform was representative of the paddock sampled. In some situations, where significant areas of distinctly different soil types occurred within a paddock, these areas were sampled independently. Examples of this (refer to Figure 1.a & 1.b) include paddock 17, which was sampled as transects 17 (Allophanic) and 17F (Gley); paddocks 31 and 32 (both predominantly Allophanic, but which had a common area of Gley soil, sampled independently as transect 31_32_F); and paddocks 1 and 2, where transects were established running across both paddocks linked to common soil types / landforms - transect 1 (Allophanic) and 2 (Gley).

Soil Cd concentrations for a soil depth of 0-150 mm were derived from the 0-75 mm and 75-150 mm data, with this data presented in Figure 1.a. Soil Cd concentration ranged between 0.48 and 1.64 mg kg^{-1} soil, with a property mean (weighted by paddock area) of 1.07 mg kg^{-1}, indicating this property would be placed within Tier 2 of the TFMS.

Soil Cd variation with soil type

Soil Cd concentrations are clearly influenced by soil type, with the Topehaehae (Gley) soils having significantly ($P < 0.001$, based on one-way Anova) lower soil Cd concentrations than the Kereone (Allophanic) soils (Figure 1.a & 1.b and Figure 2) despite common land / P-fertiliser management practices being applied across these soils types. This is supported by the consistent difference in soil Cd concentrations between Allophanic and Gley soils sampled within the same paddocks, where these were tested independently (Table 1).

Given that P-fertiliser (and therefore Cd) inputs have not been strategically varied based on soil type, differences in soil Cd concentration between these different soil types could be related to differences in Cd loss. The Topehaehae soils may have incurred greater Cd loss due to their lower specific-sorption capacity for Cd relative to the Kereone soils, which have higher organic matter content and a greater abundance of clay minerals that have a strong affinity for Cd (i.e. iron/aluminium oxides and allophane). It has been estimated that around 5-15% of fertiliser-applied Cd is leached annually (Loganathan & Hedley, 1997; Gray et al., 2003) although differences between different soil types / soil properties have been difficult to isolate (Gray et al., 2003). Future work is planned to investigate Cd distribution with soil depth and its relationship with soil mineralogy and organic matter, in contrasting soils and land management units within this property.

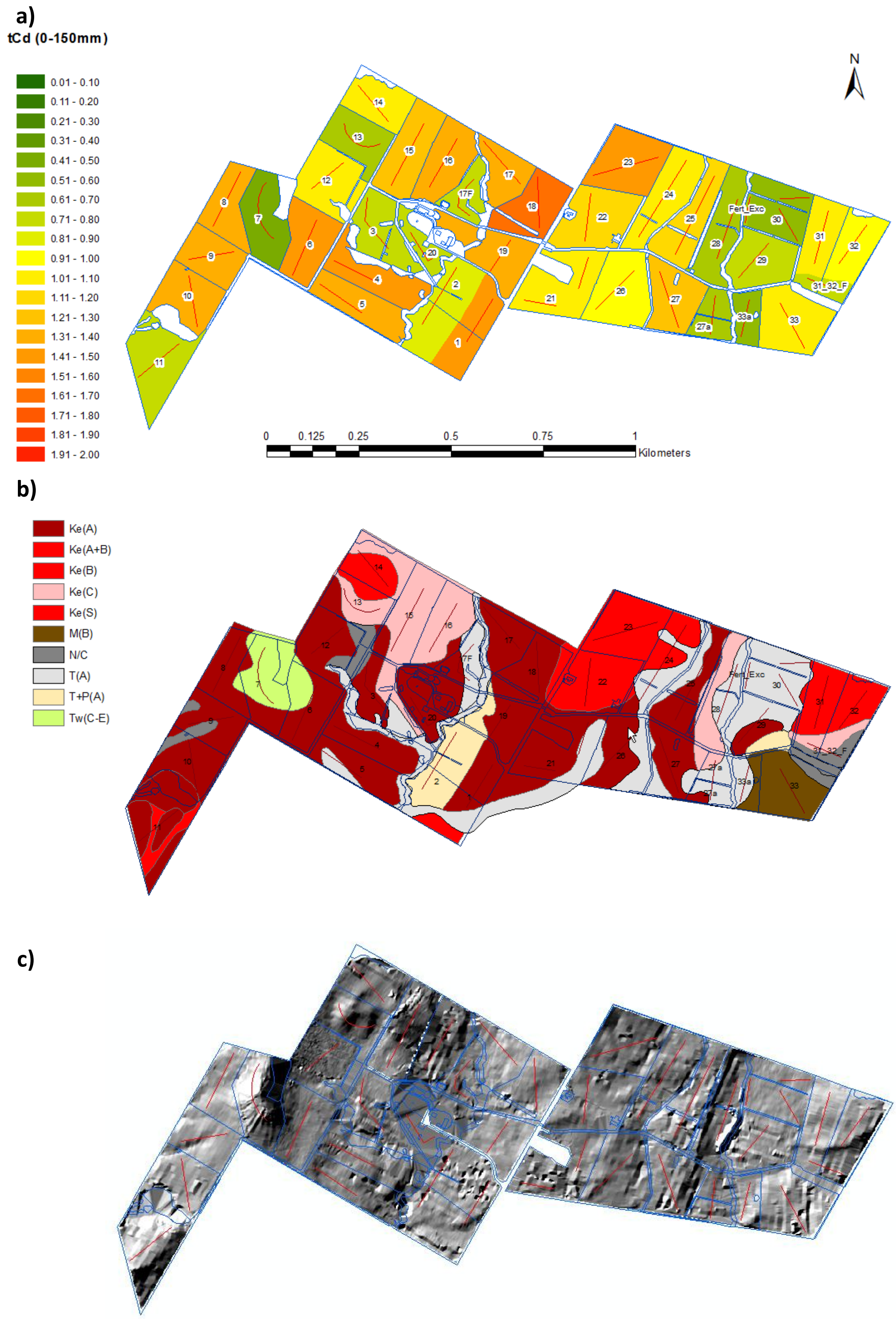

Figure 1.a) Paddock soil Cd concentrations (0-150 mm sample depth); **b)** Detailed soil map for the property (Soil type code: Ke = Kereone, T = Topehaehae, Tw = Tauwhare, M = Morrinsville, P = Pakarau. Followed by slope class: A = 0-3°, B = 4-7°, C = 8-15°; C-E = 8-25°), and **c)** ArcMap 'Hillshade' map derived from property digital elevation model, showing contour variation.

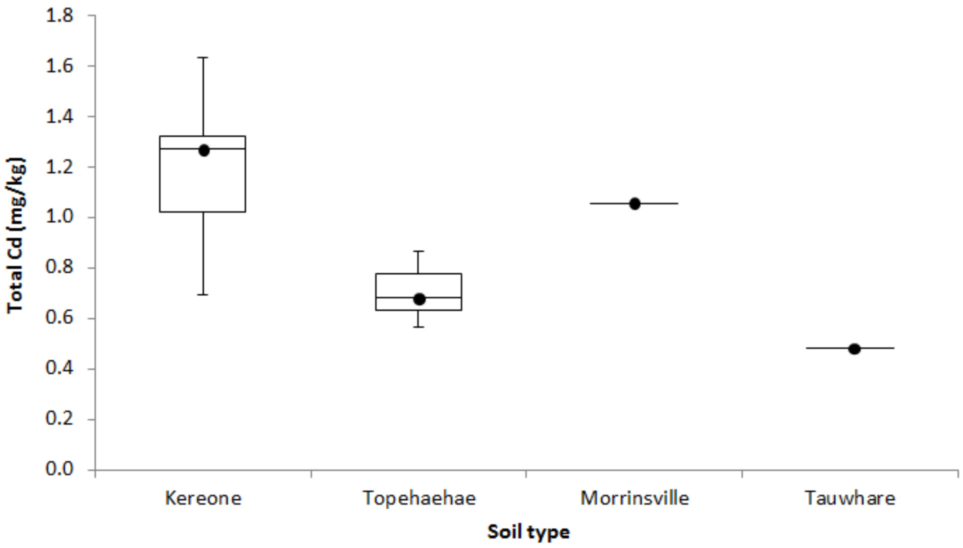

Figure 2. Interquartile ranges showing variation in total Cd results in different soil types within the property (note there is only one sample for the Morrinsville and Tauwhare soils due to small representation within the property).

Table 1. Paddocks with both Kereone and Topehaehae soil types sampled independently

Paddock	Total Cd to 150 mm depth (mg kg^{-1})	
	Kereone (Allophanic)	Topehaehae (Gley)
1 & 2	1.44 (Transect 1)	0.87 (Transect 2)
17	1.33 (Transect 17)	0.73 (Transect 17F)
31 & 32	1.02 (Transect 31) 0.95 (Transect 32)	0.79 Transect (31_32_F)

Soil Cd variation with land use history

Overall, there is a strong linear relationship (R^2 = 0.84) between soil total P and total Cd concentration (Figure 3.a). This indicates the importance of P-fertiliser application history on soil Cd enrichment, a result consistent with the observations of Bramley (1990) and Roberts et al. (1994). In contrast, there was no correlation between soil Olsen-P and total Cd concentrations (R^2 = 0.004; Figure 3.b). This is not unexpected, since the Olsen-P test only attempts to measure the 'bioavailable' fraction of the soil total P content, and the relationship between P-fertiliser inputs and Olsen-P varies due to differences in P-buffering capacity of different soils.

The total P concentrations of the Topehaehae (mean 1509 mg kg^{-1} , S.D. 117 mg kg^{-1}) and Tauwhare (1039 mg kg^{-1}, one sample only) soils were significantly lower ($P < 0.001$, based on a one-way Anova) than the total P concentrations of the Kereone soil (mean = 2598 mg kg^{-1}, S.D. = 531 mg kg^{-1}). While it is likely the Tauwhare hill soil has historically received much less P-fertiliser per unit area due to its steepness, the same cannot be said for the Topehaehae soils, which are generally flat and found in the same paddocks as the rolling Kereone soils that have much higher total P and total Cd concentration. It is possible that the lower total P concentrations for the Topehaehae soil could be related to the low P retention of the soil (approximately 35%, compared to the Kereone soil at approximately 80%) which may have resulted in greater P-loss over extended periods.

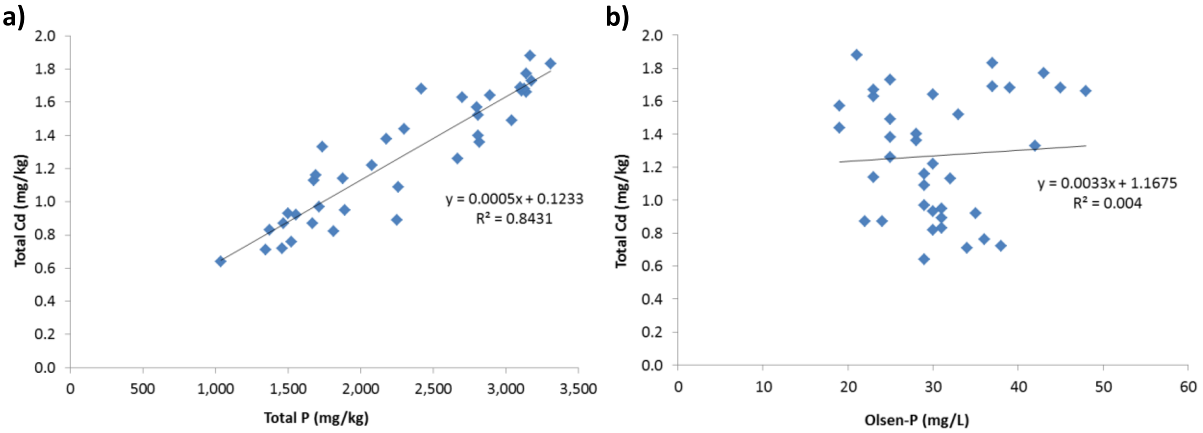

Figure 3. Relationship between soil total Cd and **a)** total P, and **b)** Olsen-P, within the property

Paddocks represented by transects 3 and 20, both on Kereone soils, have atypically low soil Cd concentrations (0.74 mg kg^{-1} and 0.77 mg kg^{-1}, respectively) relative to the majority of samples taken on this soil type (Figure 2). The atypically low soil Cd concentration for these paddocks may be explained by their land use history. Paddock 20 is a small, irregularly shaped paddock next to the original milking shed that has historically been used for holding young stock. Paddock 3, also immediately beside the original milking shed, has a history of intensive dairy shed effluent application, and due to its location it has also likely been used as a holding paddock for stock. Because of such factors, these two paddocks are unlikely to have historically received the same regularity of P-fertiliser (and therefore Cd) inputs. This is supported by their atypically low soil total P concentrations (1813 mg kg^{-1} and 1890 mg kg^{-1}, for paddocks 3 and 20, respectively) compared to other paddocks within the Kereone soil type (mean = 2598 mg kg^{-1}, S.D. = 531 mg kg^{-1}).

Soil Cd variation with slope

In addition to soil type and land use history, soil Cd concentration appears to be heavily influenced by slope, with lower soil Cd concentrations found on steeply sloping hill faces, an observation also made in hill country sheep and beef farms by Loganathan et al. (1995) and Roberts & Longhurst (2002). In particular, paddocks 11, 7 and 13 are all steep relative to the contour across the majority of the property (Figure 1.c) with these transects running across the face of the slope. The steepest landform within the property represented by the transect in paddock 7 (Tauwhare hill soil) returned the lowest soil total Cd and total P concentrations (0.48 mg kg^{-1} and 1039 mg kg^{-1}, respectively) while total Cd and total P concentrations from transects in paddock 11 (0.79 mg kg^{-1} and 1713 mg kg^{-1} respectively) and paddock 13 (0.70 mg kg^{-1} and 2250 mg kg^{-1}, respectively) are lower than the typical total Cd and total P concentrations found in other Kereone soils within the property. The lower total Cd concentrations on steep slopes relative to lower slope areas is likely due to lower P-fertiliser and therefore Cd inputs per unit area, in addition to greater Cd losses in sediment erosion and runoff. In addition, as more than 99% of ingested Cd is excreted (Lee et al., 1994; Lee et al., 1996) Cd is likely to have been transferred from the steeper slopes to the lower slopes and flat areas, where stock have a longer grazing residence time.

Intra-paddock soil Cd variability

Two paddocks within the property have been grid soil sampled to investigate within-paddock variability in soil Cd concentration; paddock 6 and paddock 18 (Figure 1.a). Kriging within the GIS package ArcMap was undertaken to provide statistical interpolation across the grid soil sampling points within these two paddock.

Paddock 18 (Figure 4) has a gentle gradient with south-west aspect. Kriging analysis across the grid soil sampling points shows a trend for greater soil Cd concentrations towards the centre of the paddock, with a definite gradient of decreasing soil Cd concentration moving towards the eastern paddock boundary. As a road borders the eastern paddock boundary, it is not surprising that the eastern section of the paddock has consistently lower soil Cd concentrations. P-fertiliser application within the roadside margin of this paddock is likely to have been limited, due to the desire of fertiliser groundspreader operators to avoid accidental application outside of the paddock margin and on to the road. Further to this, reduced stock grazing residence time near the roadside boundary will result in net-export transfer of ingested Cd, through non-uniform re-deposition in dung.

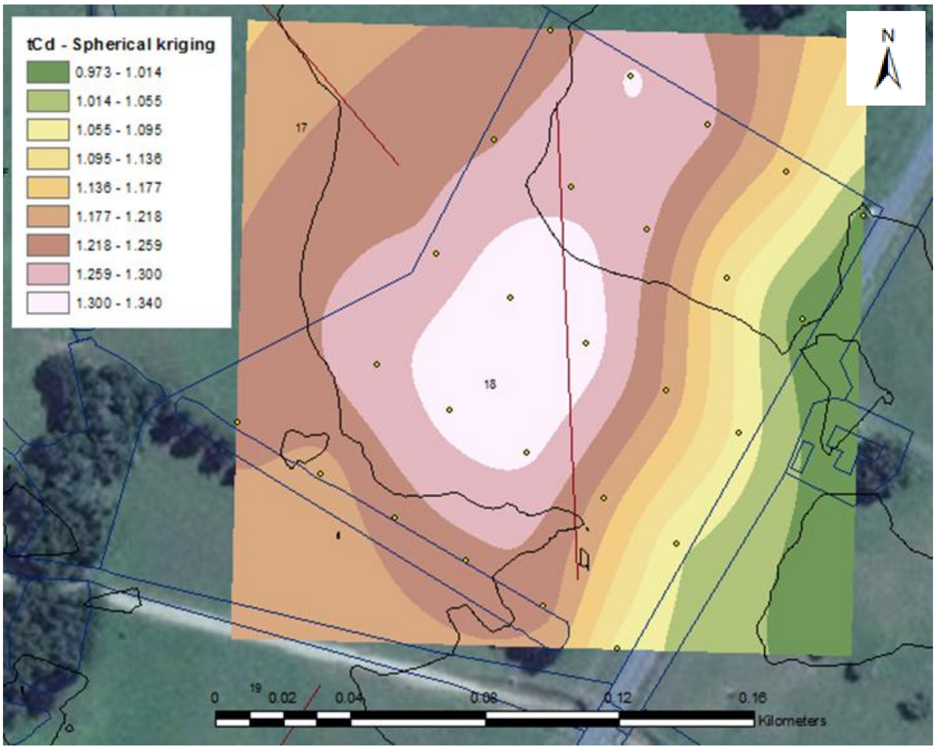

Figure 4. ArcMap kriging of grid soil sampling points within paddock 18

A portion of paddock 6 was also grid soil sampled (Figure 5). This paddock sits at the base of the steeply sloping Tauwhare hill soil in paddock 7 (Figure 1.a & 1.b). At the toeslope of paddock 7 along the north western corner of paddock 6, a reserve of large trees has been fenced off to isolate and protect a natural spring seepage area. As a consequence of this seepage, the soil along the north western edge of paddock 6 appears to be very wet for long periods. Notably, in this zone, soil Cd concentrations are consistently low, relative to those along the western paddock boundary further to the south (Figure 5).

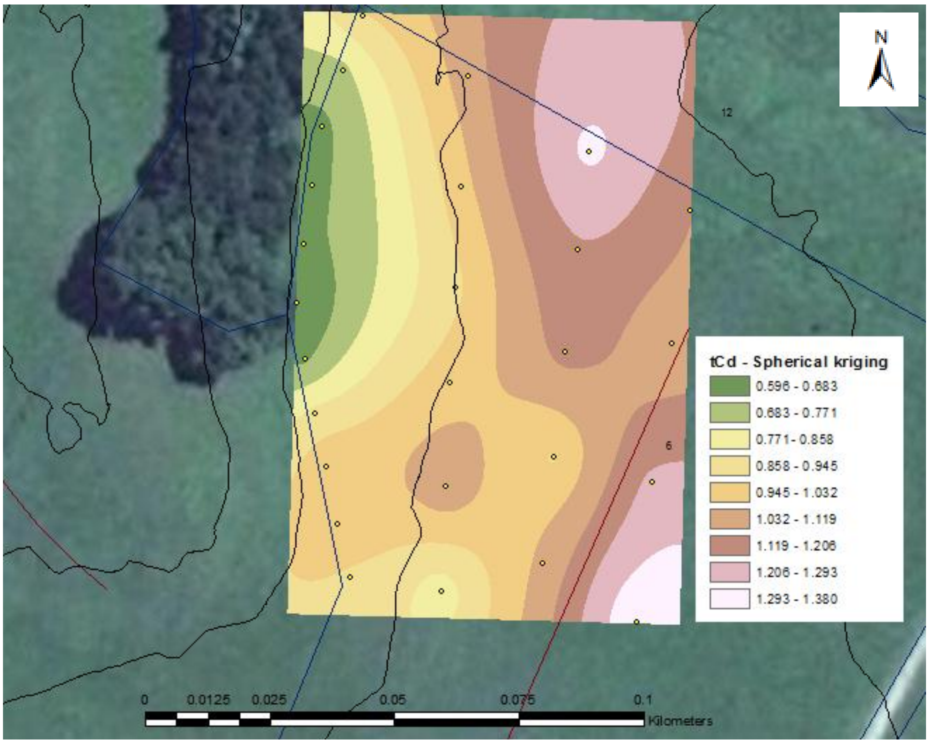

Figure 5. ArcMap kriging of grid soil sampling points within paddock 6

The lower soil Cd concentrations in the north western corner of paddock 6 beneath the bush block may be influenced by lower P-fertiliser inputs to this part of the paddock, particularly if seepage from these springs make the area unsuitable for the passage of heavy groundspreading vehicles. In addition, lack of P-fertiliser input into the bush block will mean any sediment / particulate matter moving out of the bush block and into paddock 6 will have low Cd concentration. In contrast, the higher Cd concentrations along the southern section of the western boundary of paddock 6 will have been influenced by historic P-fertiliser inputs, since this area is not affected by spring seepage. In addition, soil displacement aggravated by livestock grazing along the steep pastoral slopes of paddock 7 may lead to the gradual transfer and accumulation of Cd-enriched topsoil sediment in paddock 6.

There is a trend in paddock 6 that soil Cd concentration increases as paddock slope decreases. Again, this may be influenced by stock grazing residence time, with stock grazing the steeper slopes but moving to the flatter areas to rest, resulting in greeater dung and Cd deposition in the flatter areas. Furthermore, although not by design, it is possible that P-fertiliser application rate may have been incidentally influenced by slope, with lower and less uniform rates applied as slope increases.

Summary

There is large varibility in soil total Cd concentrations within this long term dairy farm, with soil total Cd concentration (150 mm soil depth) ranging between 0.48 and 1.64 mg kg^{-1}, with an area weighted mean of 1.07 mg kg^{-1}.

A large degree of this spatial variability is likely to be explained by differences in soil type, slope, and land management history. Soil total P and total Cd concentrations were strongly correlated (R^2 = 0.84) indicating the strong effect of P-fertiliser application history. However, total Cd and total P concentrations were also significantly ($P < 0.001$) lower in the Topehaehae (Gley) soils than the Kereone (Allophanic) soils, despite common land management and P-fertiliser history. It is possible that greater P and Cd loss may have occurred over the long term form the Topehaehae soil, due to lower P-retention and Cd specific-sorption characteristics of this soil type, relative to the Kereone soil.

Intact soil cores have been collected to 50 cm depth from this property to investigate soil Cd distribution with soil depth, and relationships with soil mineralogy and organic matter content. A second property (Canterbury) with contrasting soil types is also being included in the evaluation to understand spatial and depth variation of soil Cd in long term dairy farms.

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