Physiographics of Southland
Part 1:
Delineation of key drivers of regional hydrochemistry and water quality

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Technical Report

June 2016

Rissmann, C., Rodway, E., Beyer, M., Hodgetts, J., R., Snelder, T[a]., Pearson, L., Killick, M., Marapara, T. R., Akbaripasand, A., Hodson, R., Dare, J., Millar, R., Ellis, T., Lawton, M., Ward, N., Hughes B[a]., Wilson K[b]., McMecking, J., Horton, T[c]., May, D., Kees, L.

[a]LWP Ltd; [b]Landpro Ltd; [c]Geological Sciences, University of Canterbury

Publication No 2016/3

Version 1 - Preliminary

Document Quality Control

Environment Southland Division:	Environmental Information		
Report reference:	Title: Physiographics of Southland Part 1: Delineation of key drivers of regional hydrochemistry and water quality	No:	2016/3
Prepared by:	Rissmann, C., Rodway, E., Beyer, M., Hodgetts, J., R., Snelder, T., Pearson, L., Killick, M., Marapara, T. R., Akbaripasand, A., Hodson, R., Dare, J., Millar, R., Ellis, T., Lawton, M., Ward, N., Hughes B., Wilson K., McMecking, J., Horton, T., May, D., Kees, L.		
Illustrations by:	Hodgetts, J.	**Maps produced by:**	Rodway, E., Beyer, M.
Reviewed by:	Peter Almond[1], Troy Baisden[2], Vincent Bidwell[3], Chris Daughney[2], Bill Dyck[4], Allan Hewitt[5], Clive Howard-Williams[6], Scott Larned[6], Matthew Leybourne[7], Mike Scarsbrook[8], Hanspeter Schreier[9], Ranvir Singh[10], Trevor Webb[5], Jenny Webster-Brown[11]; Southland Science Technical Advisory Group[12]. 1. Soils and Physical Sciences, Lincoln University 2. GNS Science 3. Vincent Bidwell Consulting 4. Bill Dyck Ltd 5. Landcare Research 6. NIWA 7. Department of Earth Sciences, Laurentian University 8. Dairy New Zealand 9. Professor Emeritus, Land and Water Systems, University of British Columbia 10. Massey University, Institute of Natural Resources 11. Waterways Centre for Freshwater Management, University of Canterbury and Lincoln University 12. Southland Science Technical Advisory Group comprised of National and International Experts advising on the Southland Science Programme. Members: Dr Clive Howard-Williams, NIWA; Dr Chris Daughney, GNS; Dr Murray Close, ESR; Dr Cath Moore, GNS/ESR; Dr Liz Wedderburn, AgResearch; Prof. Jenny Webster-Brown, University of Canterbury; Associate Prof. Peter Almond, Lincoln University; Dr Mike Scarsbrook, DairyNZ; Dr Vince Bidwell (independent consultant); Bill Dyck, Envirolink Coordinator.		
Approved for issue by:	Graham Sevicke-Jones Director, Science and Information		
Date issued:	1 June 2016	Project Code:	4065.1446

Document History

Version: 1	**Status:** Preliminary
Date: June 2016	**Doc ID:**
Disclaimer:	This report has been prepared in good faith within time and budgetary limits. Due to time constraints we have not been able to incorporate all review feedback. These limitations will be addressed in a later review and a subsequent version published.

Physiographics of Southland
Part 1:
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Technical Chapter 3:
Soil Chemistry

June 2016

Rissmann, C., Pearson, L., Killick, M., Rodway, E., Beyer, M., Marapara, T. R., Hodgetts, J.

Document Quality Control

Environment Southland Division:	Environmental Information		
Report reference:	Title: Technical Chapter 3: Soil Chemistry		No: 2016/3
Prepared by:	Rissmann, C., Pearson, L., Killick, M., Rodway, E., Beyer, M., Marapara, T. R., Hodgetts, J.		
Key Technical Reviewers:	Hewitt, A., Almond, P., Webb, T., Schrier, H.		
Technical Illustrations by:	Hodgetts, J.	**Maps produced by:**	Rodway, E., Beyer, M.
Technical Editors:	Hodgetts, J., Lovett, A., Lawton, M.		
Approved for issue by:	Graham Sevicke-Jones Director, Science and Information		
Date issued:	1 June 2016	Project Code:	4065.1446

Document History

Version: 1	**Status:** Preliminary
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TC3 Soil Chemistry

TC3.1 Introduction

Soils play a critical role in the hydrochemical evolution of ground and surface waters (Olson, 2012; Daughney et al., 2015; Rissmann, 2015). Soil and rock minerals are the first mediums of interaction when precipitation infiltrates or runs off the landscapes (Smith & Monaghan, 2003; Rissmann et al., 2015). Even precipitation moving across bare rock, scree or talus in Alpine areas undergoes remarkable changes in its chemical composition over short distances (Zobrist and Drever, 1990; Clow and Drever, 1999; Drever, 2002). For example, thin, CO_2 rich soils are often rapidly weathered and leached of soluble minerals by infiltrating precipitation. This results in acidic waters that are high in carbonic acid recharging the groundwater (Daughney et al., 2015; Essington, 2015).

The degree to which infiltrating precipitation is influenced by the soil zone is a factor of the physical and chemical composition of the soil. Soil texture, structure and depth all influence the residence time of water in contact with the soil, as does the presence (or otherwise) of artificial drainage. Spatial changes in gross soil chemical characteristics equate to considerable differences in the chemical composition of soil drainage (TC 4). The pathway through which water moves through a soil (e.g., interflow or artificial drainage, overland flow or vertical percolation to underlying aquifers) also influences the chemical composition of soil drainage (Smith and Monaghan, 2003; Rissmann et al., 2012; Monaghan et al. in press). In addition, the chemical composition of infiltrating water and its residence time determine the rate of chemical weathering of soil and rock minerals, which in turn influences the chemical composition of soil and recharge water (Rissmann et al., 2015; Daughney et al., 2015; Essington, 2015).

In this chapter, we assess the chemical variation in Southland's soil chemistry and its major drivers using data available through the Topoclimate South soil mapping survey, the General Survey of the Soils of the South Island and a number of statistical techniques. The main objective of this chapter is to develop a conceptual understanding of the controls over soil chemical variability at a regional scale. The variation of soil chemistry and its drivers is important when determining the relationship between soil and soil water chemistry and the spatial pattern of surface and groundwater chemistry across the region as demonstrated in subsequent chapters (TC 4 to TC 8).

TC3.2 Southland Soil Chemical Data

TC3.2.1 Spatial mapping

Soil chemical data was sourced from the Topoclimate South Soil Survey (2001) and the earlier General Survey of the Soils of the South Island (DSIR, 1968). To produce regional maps of soil chemical properties data from individual soil profiles was weighted by horizon depth, averaged for the profile and then averaged across all profiles for each soil series based on the New Zealand soil classification (NZSC) (Hewitt, 1993). We assumed soil chemical properties are characteristic of the soil series in which they are found, though soil series are often only defined by field visual characteristics which include profile form, colour and texture. Averaged properties were also assigned to soil series in areas from which no samples were analysed, however this approach adds some uncertainty.

Series averages were then attributed to each soil in the locations where it was mapped as GIS polygons. The soil series polygons defined in the Topoclimate South, Soils of Wallace County (O'Byrne, 1986) and the Land Resource Inventory (LRI) survey maps were used, in that order of preference (Soils of Wallace County refined the mapping of the earlier LRI survey, but added no new chemical data). Figure 3-1 shows the NZSC Order (Hewitt, 1993) for Southland soils from the combined surveys.

We note that some soil series showed considerable variation in chemical properties of profiles from different locations. This raises questions about the appropriateness of assigning soil series information derived from one location to another as parent materials may be different. The same applies to soils where type locations or profiles are used to assess average soil hydrological properties which are then extrapolated to other, often very different locations. Due to these issues the soil chemical maps established in the following will be subject to uncertainty. However, they are fundamental to establish a better understanding of soil hydrology and soil chemistry in Southland and ultimately relate these to the water chemistry and water quality outcomes that these maps will guide.

TC3.2.2 Chemistry of Southland soil

In the following we discuss the spatial distribution of soil chemistry in Southland including pH, cation exchange capacity (CEC), base saturation (BS), total exchangeable bases (TEB), cation concentrations and carbon (C) and nitrogen (N) content. Definitions of these terms are given in Appendix B.

The **pH** of Southland's soils are typically moderately acidic (mean 5.8) with a range from extremely acidic (4.2) to moderately alkaline (7.9) (Figure 3-2a). Soils with the lowest pH are the Podzol soils of Fiordland and the Catlins, whilst soils in the Southland Plains (especially soils with ultramafic parent materials) are generally associated with higher soil pH (Figure 3-2a).

Cation exchange capacity (CEC) is associated with clay and organic matter in soils. In Southland, high CEC is mostly evident in high country soils under native vegetation, which have accumulated organic matter on or in the topsoil (Figure 3-2b). CEC in agricultural soils are more influenced by clay content, but clayey soils are less prevalent, accounting for less than 25% of Southland's soil cover.

Base saturation (BS%) and total exchangeable bases (TEB) is highest in soils formed in sandstone sediments from the Brook Street terrane of the Takitimu Range and the Caples terrane of the northern Southland ranges, where there is also some contribution from the ultramafic rocks of the Dun Mountain-Maitai terrane (Figure 3-2c and Figure 3-1b). These sediments form part of the river flats and terraces of the major Southland catchments: the Waiau, Aparima, Oreti and Mataura. Base cations from these parent materials accumulate in soils through weathering, especially where leaching is limited. Leaching can be limited either through complexation of the cations with organic matter (e.g. in Melanic soils) or by drainage limitation (e.g., in Organic and Gley soils). Recent soils may also have high BS% despite relatively low concentration of total exchangeable bases (TEB) and low acidity (Figure 3-2d). Since Organic, Gley, Melanic, and Recent soils and their sedimentary parent materials are found mainly in the lowlands, BS% in these areas is generally higher (Figure 3-1). There are a few instances however, where high BS% can be found in hilly or mountainous country, for example in soils of the limestone outcrops north and east of Winton, and in the southern Eyre Mountains where the Dun Mountain-Maitai terrane outcrops. Most soils in Southland have low TEB, orin the northern and central plains, moderate TEB. The few areas of high TEB are localised and closely associated with basic sediments.

Cation concentrations: Looking in more detail at the individual base cations illustrated in Figure 3-3a and Figure 3-3b, it is evident that distributions of Ca and Mg are related to that of TEB. This makes sense as Ca and Mg are generally the bases of highest concentration overall. The high BS% in an area of the southern Eyre Mountains can be linked to high concentrations of Mg and to a lesser extent, K rather than Ca. In the limestone area north and east of Winton high BS% can be linked to high Ca rather than Mg. Both Ca and Mg concentrations are high around the southern Takitimu Mountains (Brook Street terrane). Unlike Ca and Mg, K concentration is high in Fiordland and generally elevated in the high country soils than in the soils of the plains (Figure 3-3d). This appears to be a function of the parent rocks (Median Batholith) exposed in those areas, rather than associated with soil processes.

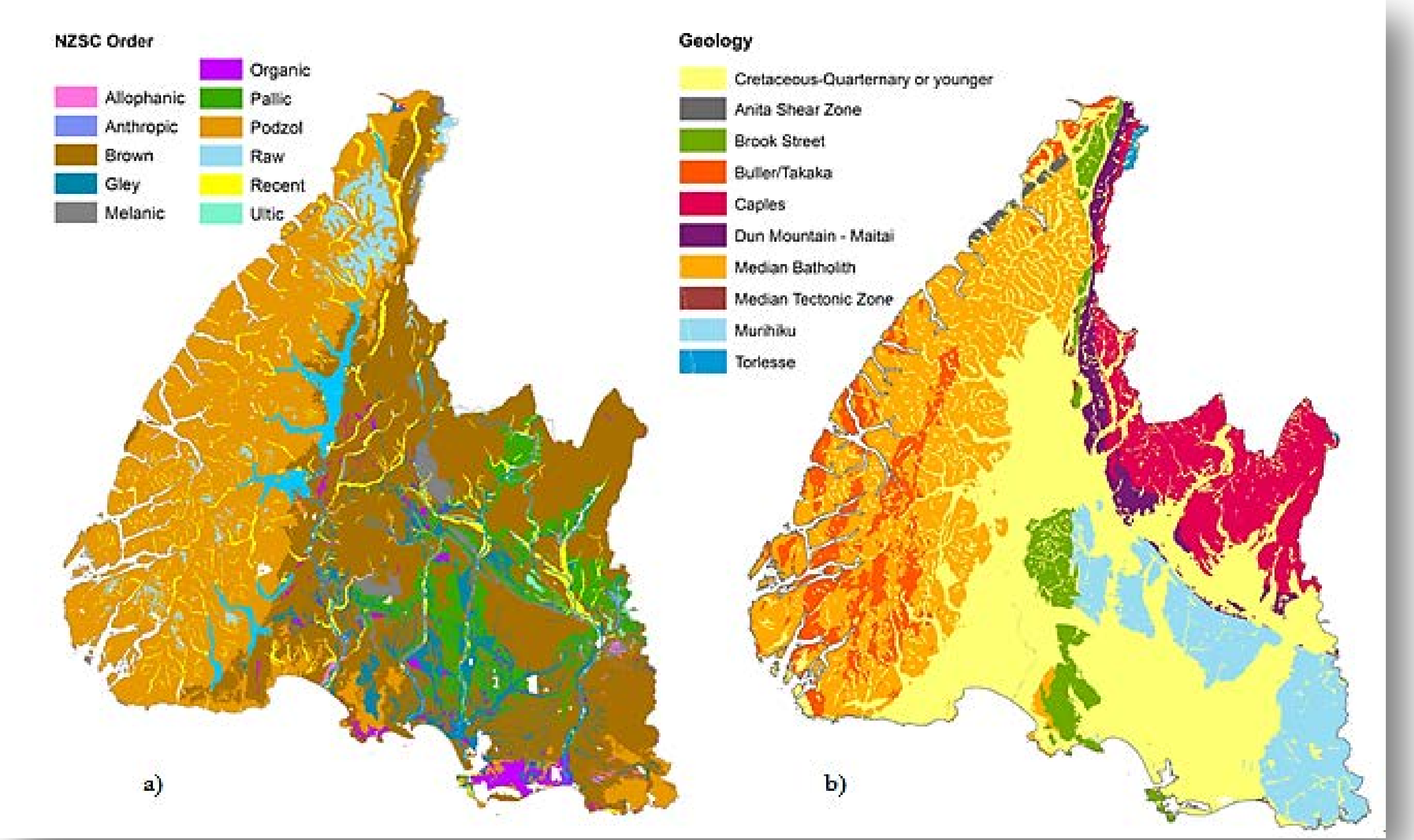

Figure 3-1: a) Soil by NZSC Order (Topoclimate South, 2001; LRI, 1968), and b) Geology of Southland Qmap (Heron, 2014).

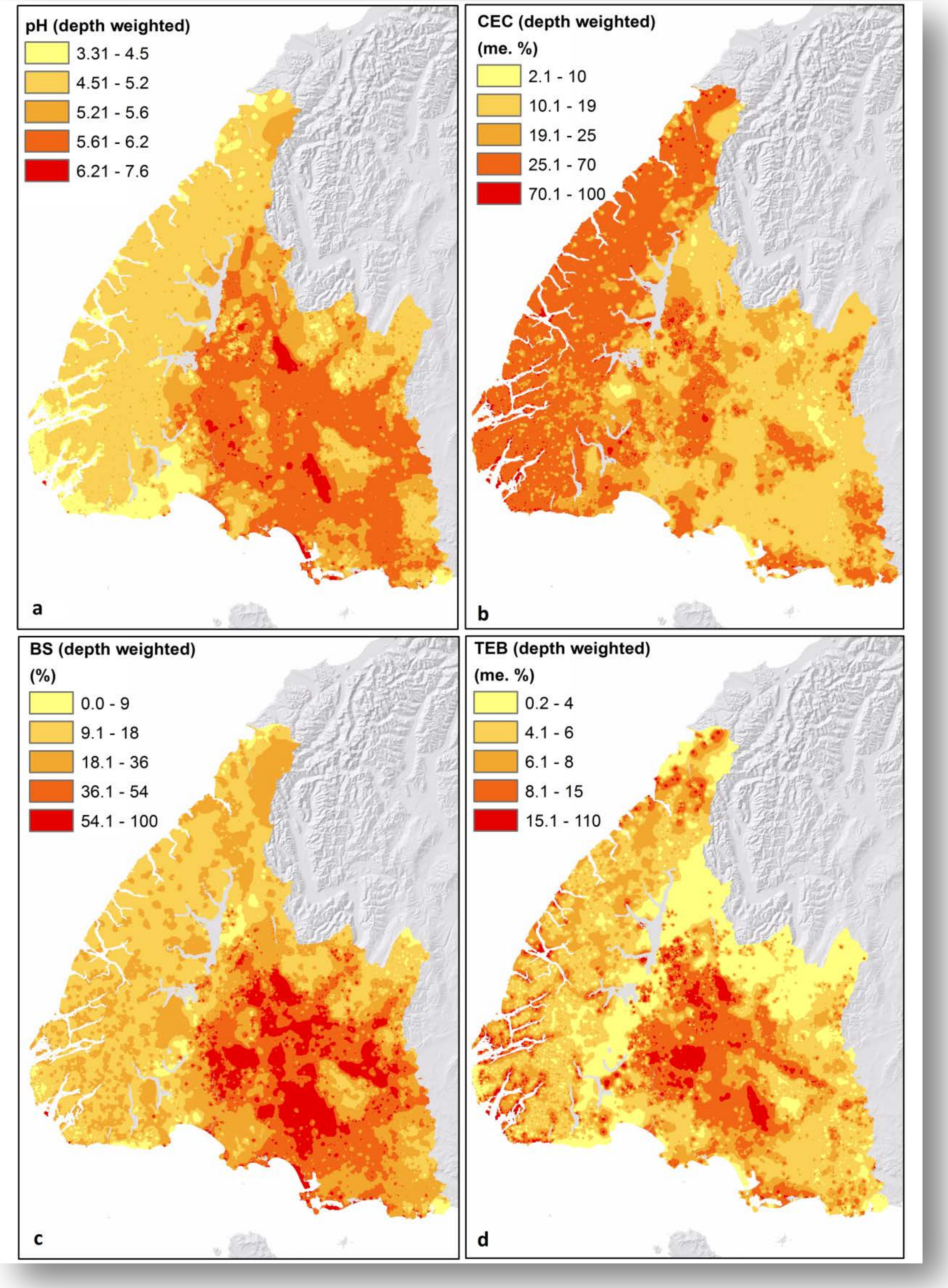

Figure 3-2: Spatial distribution of a) pH, b) cation exchange capacity, c) base saturation, and d) total exchangeable bases.

Data relating to soil Na content was unavailable for some areas, notably most of Fiordland; therefore mapping of Na was limited to areas where data was available. Na shows two patterns of distribution in the soil landscape: a gradient of decreasing concentration with distance from the coast, likely related to deposition of marine Aerosols (described in TC 1 and TC 2), over which is superimposed a strong, patchy distribution related to relatively Na-rich parent materials (Figure 3-3c). One of these high Na areas is located around the southern Takitimus where the other base cations (Ca, Mg, and K) are also high. The other areas with high Na concentrations in soil are around the eastern fringes of the Fiordland mountain ranges where data is available, and around Te Anau. This may be related to sediments from the Livingston and Thompson Mountains to the north for which data is also limited. If we limit the data to the Topoclimate South soil survey the picture is clearer with a strong, seemingly exponential, gradient in exchangeable Na decline with distance from the southern coast, which mimics the rainout of marine aerosolic Na described in TC 1 and TC 2.

Carbon content (C%) is highest in Organic and Podzol soils (Figure 3-4a). In the Organic soils, organic matter provides the main parent material of the entire soil profile. In Podzols mineral matter provides the main parent material. Carbon in these soils may be concentrated in an organic horizon at the surface and/or may have accumulated in subsoil horizons through leaching of the organic horizon at the surface.

Nitrogen content (N%), despite being a macronutrient for pasture and crop growth, is also highest in Organic and Podzol soils as a constituent of naturally accumulated organic matter, rather than in agricultural soils as a result of high N inputs associated with fertilizer application and manure deposition. However, in the Podzol soils N% is not as high as C%, suggesting lower humification (low microbial activity) of fresh organic matter under cold, acidic conditions. Very high N% is confined to Organic soils (Figure 3-4b).

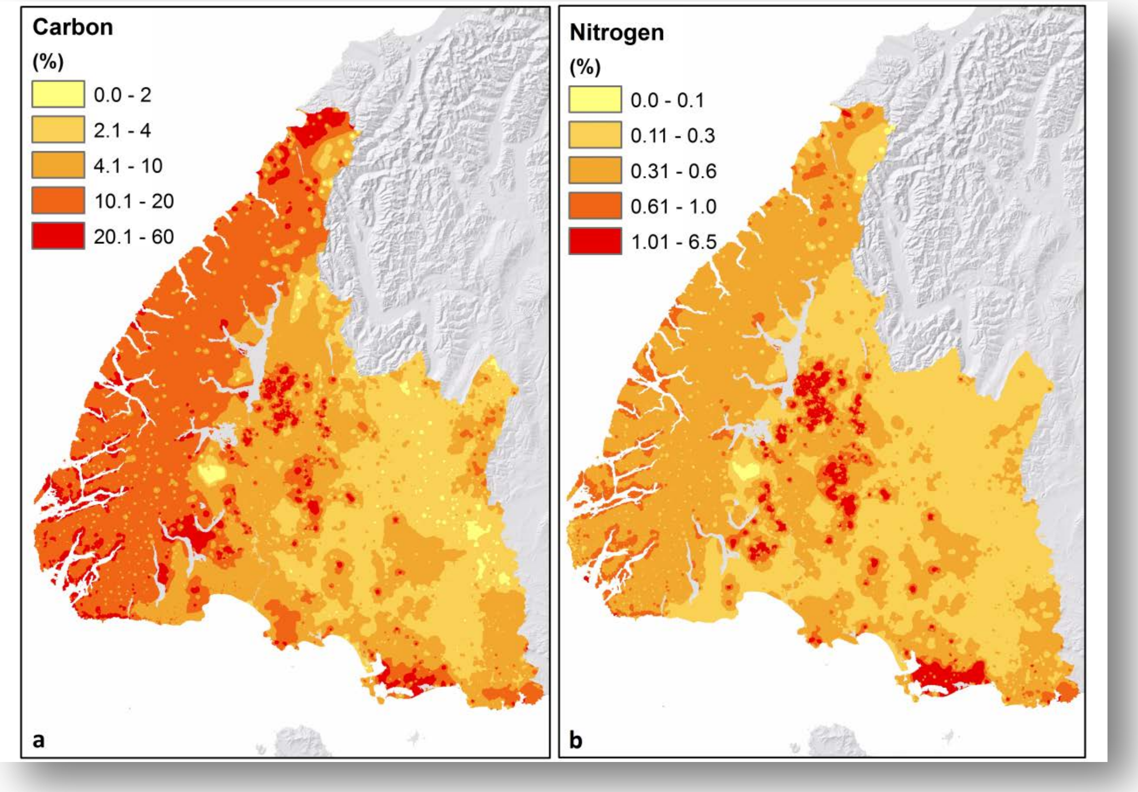

Figure 3-3: Spatial distribution of a) carbon, and b) nitrogen content of soil.

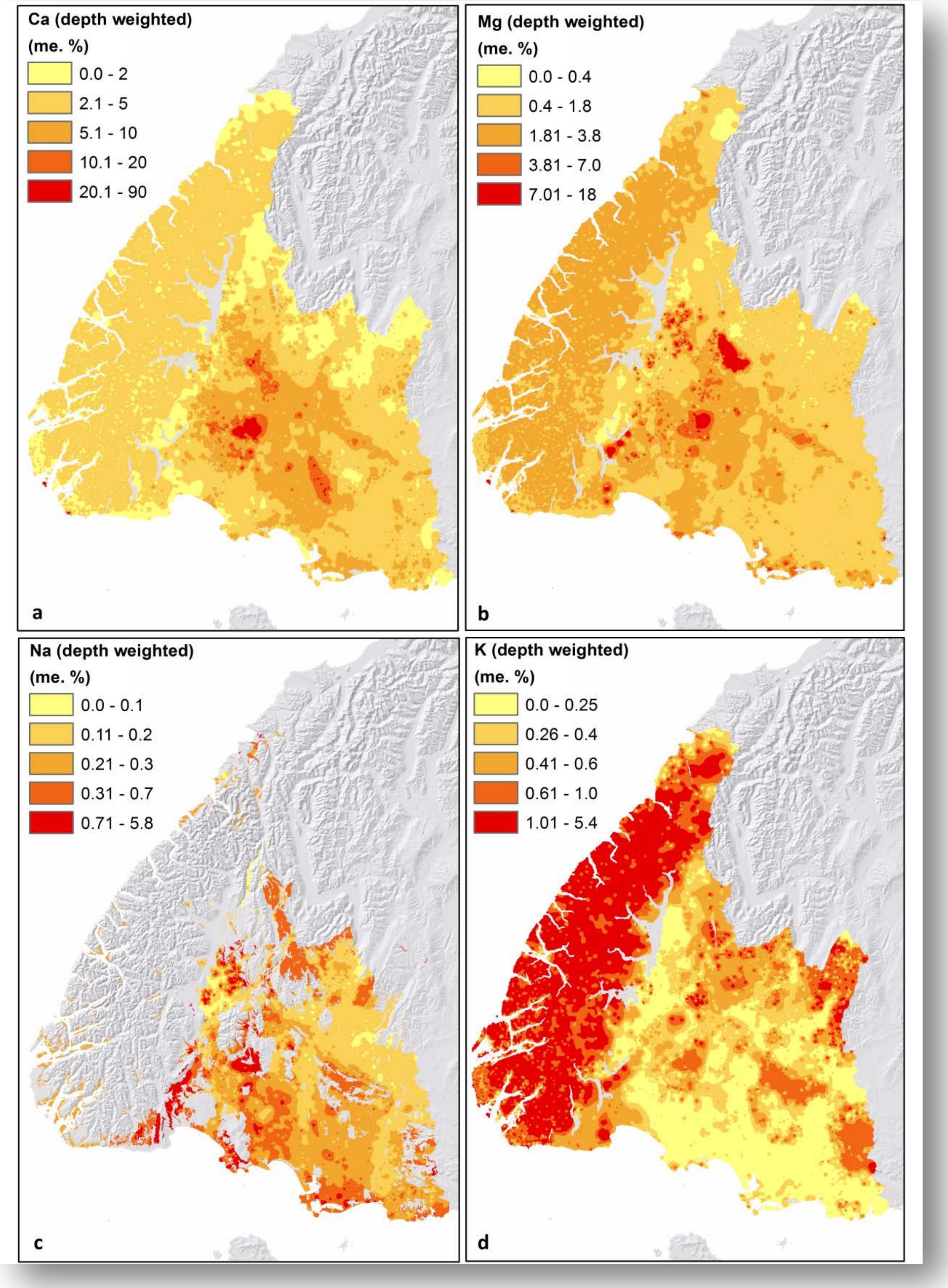

Figure 3-4: Spatial distribution of a) calcium, b) magnesium, c) sodium, and d) potassium. Note: sodium data set is limited and spatial distribution has been clipped to where data is available.

TC3.2.3 Soil Hydrology

The evolution of soil, i.e. landform type and landform age, affects not only the chemistry of the soil, but also its hydrology, specifically its permeability. Understanding soil permeability and drainage is important as it also affects the chemical evolution of Southland's freshwater (TC 6). Specifically, it will be shown that redox state and soil denitrification potential of the soil zone are linked to soil permeability and soil drainage. The permeability and drainage of Southland's soil can be defined on the basis of permeability classes (Clayden and Webb, 1994) and soil drainage classes (Hewitt, 1993; Milne et al., 1995) respectively. For simplification, both were combined in a Soil Permeability and Drainage (SPD) Rating summarised in Table 3-1 and Figure 3-5. For example, very poorly-drained soils that have a moderate to slow permeability are assigned a very high SPD.

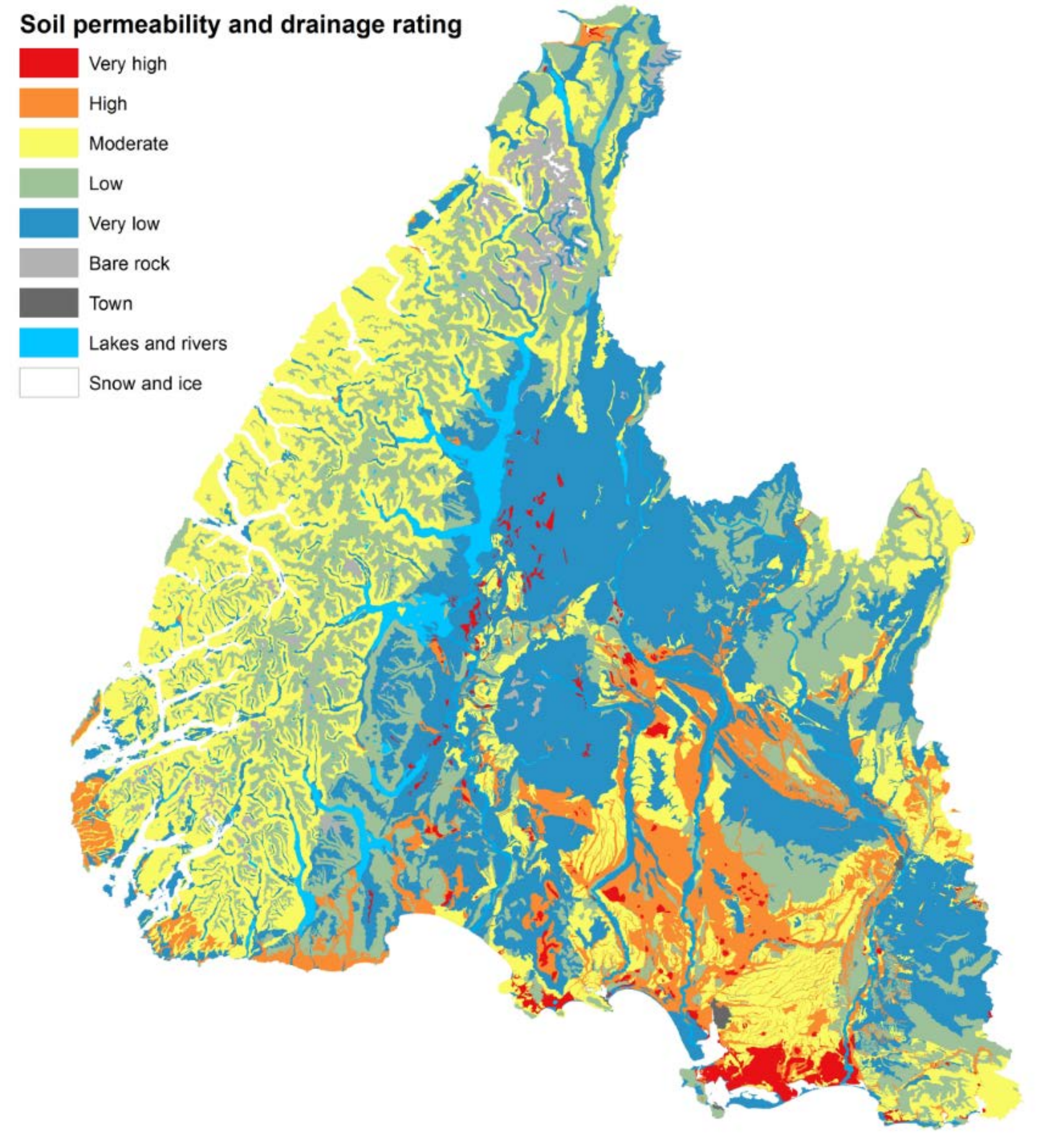

Figure 3-5: Map of Soil Permeability and Drainage rating (SPD).

Table 3-1: Soil Permeability and Drainage Rating

SPD Rating	Drainage Pattern (if present)	Permeability	Drainage class
Very high	Conventional	Slow	Very poor
		Moderate	Very poor
High	Mix of conventional and contour (slope dependant)	Slow	Poor
		Moderate	Poor
		Rapid	Poor
Moderate	Mix of conventional and contour (slope dependant)	Slow	Imperfect
		Moderate	Imperfect
		Rapid	Imperfect
		Slow	Moderately well
Low	Contour and soak hole (flat only)	Rapid Moderate	Moderately well Moderately well
		Slow	Well
Very low	Typically feeder drains from other areas	Rapid	Well
		Moderate	Well

Soil drainage class in conjunction with an understanding of organic carbon contents provide the basis for predicting soil zone reduction or 'denitrification' potential (Hewitt, 1993; Killick et al., 2015). In almost all instances we consider soils to have more than enough high quality organic carbon, at least within the topsoil, to drive reduction. However, redox evolution towards NO_3 reducing conditions takes time and is inhibited in the presence of O_2 so that well-drained soils seldom exhibit reducing signatures (redoximorphic characteristics), whereas imperfect to very poorly- drained soils do (Hewitt, 1993; Webb et al., 2010; Killick et al., 2015;). Therefore, soil drainage class in conjunction with organic carbon content, horizon thickness, and soil depth is considered a good proxy of denitrification potential as demonstrated in TC 6.

TC3.3 Principal Component Analysis of Southland's Soil Chemical Data set

Exploratory relationships of fundamental soil chemical characteristics and drivers of spatial patterns were assessed using Principal Component Analysis (PCA). PCA was carried out on log10 transformed, z-scored soil chemical data for Southland (profiles from Topoclimate South) including: pH[1], CEC (meq%), soil BS%, exchangeable Ca (meq%), exchangeable Mg (meq%), exchangeable Na (meq%), exchangeable K (meq%), organic C%, N content (N%), carbon to nitrogen ratio (C:N), clay content (Clay%), phosphate retention (%) and soil drainage class (Table 3-2). Where data was available for all horizons of the profiles, the soil chemical properties were depth weighted by horizon and averaged for each of the 412 different profiles. Clay%, P-retention, C%, N% and C:N ratio were not depth-weighted as data for these properties was commonly available for only a limited portion of the profile, typically the A horizon and occasionally another horizon. Therefore, these properties were calculated as simple averages or single values.

As with all of the analysis undertaken, cumulative probability plots and a fundamental knowledge of soil chemical characteristics were used to remove outliers from the data set. Multiple PCA runs were undertaken during which variables such as Clay%, Gravel%, P-

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[1] There was no need to log10 transform pH.

retention, BS%, drainage class and denitrification potential (SDNP) were swapped in and out in order to weight the possible confounding influences over the output[2]. SDNP rankings of soils by Killick et al. (in prep) were not included in the PCA and HCA analyses of chemical data described in the following Technical Chapter (TC 3.4), but are discussed in the context of those results in TC 3.6.

Table 3-2: Horizon weighted soil chemical properties.

	Valid Cases	Mean	Median	SD	CV	Min	Max	Range
DW pH	412	5.8	5.8	0.4	0.1	4.3	7.7	3.4
DW CEC	412	16.4	13.9	9.5	0.6	2.1	85.1	83.0
DW TEB	412	7.6	6.2	5.8	0.8	0.6	51.6	51.0
DW BS %	412	45.4	43.2	22.8	0.5	5.3	128.5	123.2
DW Ca	412	5.8	4.7	4.7	0.8	0.2	44.8	44.5
DW Mg	412	1.4	0.9	1.4	1.0	0.1	9.4	9.3
DW K	412	0.3	0.2	0.3	1.3	0.0	2.9	2.9
DW Na	412	0.2	0.2	0.2	0.8	0.0	1.4	1.4
Av_P_retent	412	41.3	37.0	18.4	0.4	2.0	96.4	94.4
Av_Clay%	412	16.7	16.7	6.2	0.4	1.6	36.0	34.4
Drainage	412	3.3	3.0	1.3	0.4	1.0	5.0	4.0
SDNP	409	0.4	0.3	0.3	0.7	0.0	1.3	1.3

Five principal components with Eigenvalues > 1.0 explain 81 % of the variance in the data. PCA results are summarized in the variance table (Table 3-3) for the whole dataset and eigenvector table (Table 3-4) for each variable.

Table 3-3: PCA variance table, with significant Eigenvalues (>1) shown in red. Variables were selected using z-scored and log10 transformed data, except for pH: DW_pH, DW_CEC, DW_BS pct, DW_Ca, zLog10DW_Mg, DW_K, DW_Na, Av_C, Av_N, C2N_ratio, P_retent, Clay%, and Drainage.

Component No	Eigenvalue	Cumulative Variance	Percent (%)	Cumulative (%)
PC 1	3.59	3.59	28	28
PC 2	3.10	6.69	24	51
PC 3	1.48	8.18	11	63
PC 4	1.23	9.40	9	72
PC 5	1.13	10.53	9	81
PC 6	0.77	11.30	6	87

TC3.3.1 Principal Component 1 – Degree of Soil Weathering

Principal Component 1 (PC1) explains 28% of the variance and displays positive weightings for CEC, Ca, Mg, Na and K, C% and N%, and P-retention for Southland soils. pH is negatively

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[2] Percent gravel was not included in the initial run because only a limited number of soils contained stones which severely limited the data set when including gravel percent in PCA. Swapping Clay% in an out of the PCA caused significant differences in the number of significant components (i.e., Eigenvalues > 1) and hence data resolution. Clay% was retained as a key variable in the PCA. SDNP was considered to be double accounting with drainage class and C% and was not included in the PCA.

weighted and declines as the PC1 weightings become more positive. As soils weather, pH values decline as does Ca content and BS%, whereas Al and Fe oxides/oxyhydroxides accumulate resulting in increased anion exchange capacity or P-retention. PC1 is therefore indicative of soil weathering with the most weathered mineral soils or acidic organic soils forming one end of a continuum (strongest positive weighting for PC1) and recent soils the other (strongest negative weightings for PC1; Figure 3-6).

Table 3-4: PCA eigenvectors table, with significant values (> 0.3 or <-0.3) shown in red. Variables selected using z-scored and log10 transformed data, except for pH: DW_pH, DW_CEC, DW_BS %, DW_Ca, DW_Mg, DW_K, DW_Na, zLog10Av_C, Av_N, C2N_ratio, P_retent, Clay% and Drainage.

	PC 1	PC 2	PC 3	PC 4	PC 5
DW_pH	-0.20	0.34	0.24	0.11	0.26
DW_CEC	0.48	-0.02	0.05	0.15	-0.01
DW_BS %	0.04	0.53	0.05	-0.15	0.09
DW_Ca	0.28	0.39	0.17	-0.07	0.26
DW_Mg	0.33	0.34	-0.15	0.01	-0.26
DW_K	0.27	0.08	0.25	0.12	-0.58
DW_Na	0.33	0.10	-0.23	0.15	-0.24
Av_C	0.37	-0.28	0.18	-0.33	0.18
Av_N	0.35	-0.15	0.43	-0.18	0.30
C2N_ratio	0.12	-0.28	-0.37	-0.31	-0.14
P_retent	0.21	-0.32	0.03	0.50	0.25
Clay%	0.15	0.10	-0.41	0.50	0.34
Drainage	-0.17	-0.13	0.50	0.41	-0.27

TC3.3.2 Principal Component 2 – Acid vs. Base Parent Material

Principal Component 2 (PC2) explains 24% of the variance in the data and displays the strongest positive weightings for BS%, Ca, Mg and pH (Table 3-4 and Figure 3-7). Importantly, the C:N and P-retention are negatively weighted relative to pH and BS%. On the basis of these findings, PC2 is indicative of soil parent materials (PM) and their influence over soil chemistry. Soils formed in base rich PM (i.e., calcareous, basaltic and mafic/ultramafic tuffaceous lithologies) determine one end of a continuum (positive weighting for PC2), while soils formed in felsic PM (i.e., granitic or quartzitic) determine the other (strongest negative weightings for PC2). Recent soils, irrespective of their PM, have weightings that cluster around 0.5 for PC2, suggesting that a degree of weathering is required before the influence of PM is expressed.

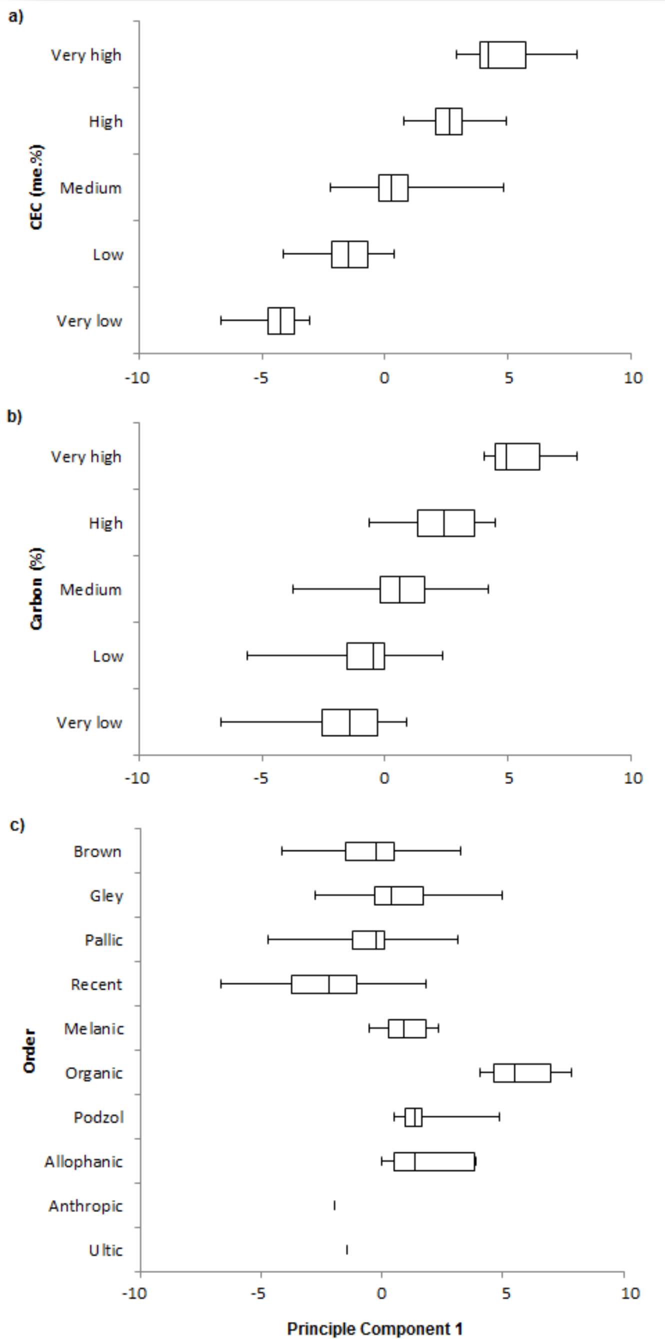

Figure 3-6: Principal Component 1 by a) CEC, b) organic carbon, and c) soil order.

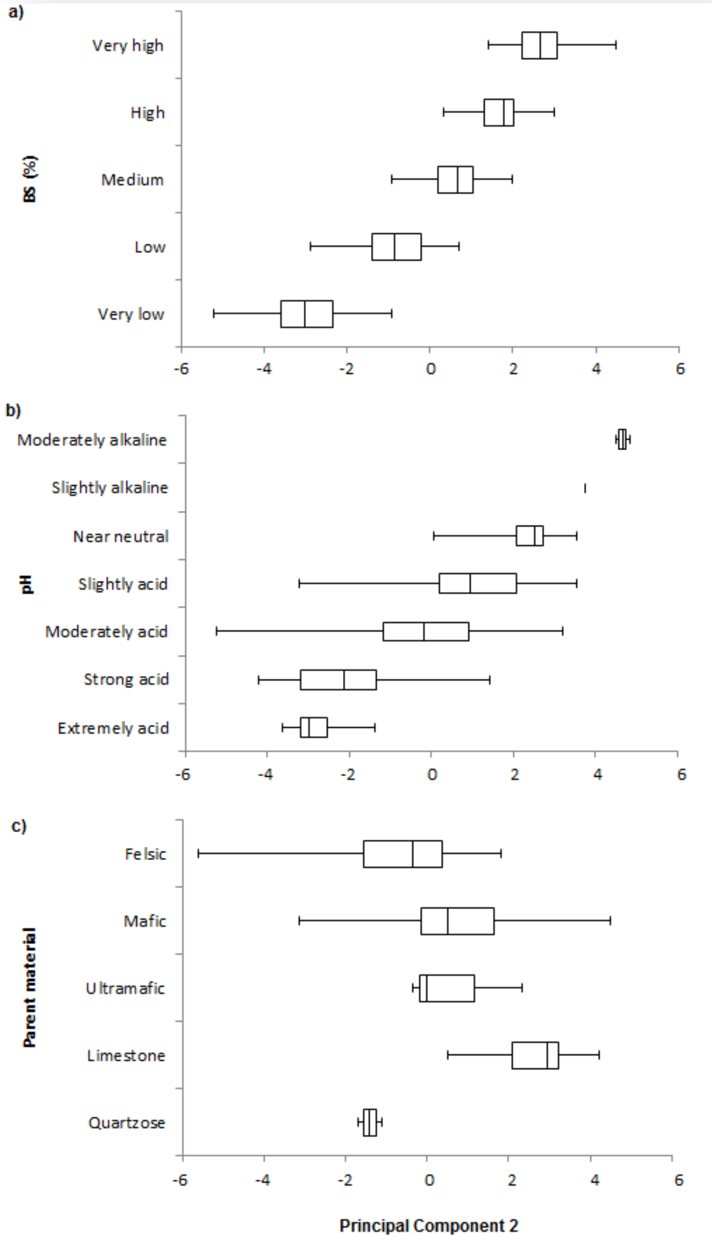

Figure 3-7: PC2 by a) base saturation, b) soil pH, and c) parent material (note that peat is not included as a rock class for parent materials), sourced from S-Map (Landcare Research, 2016).

TC3.3.3 Principal Component 3 – Drainage

Principal Component 3 (PC3) explains 11% of the variance in the data with the strongest positive weightings for drainage class and N% and lesser positive weightings for pH and K (Table 3-4). Also apparent is a strongly negative weighting for Clay%, C:N ratio and a lesser negative weighting for Na. No significant weightings occur for Ca and Mg or CEC reflecting equivalence between the two ends of the continuum for these parameters. Soils with the strongest positive weightings (i.e. >1.5) for PC3 comprise predominantly well-drained soils with low clay content. Soils with a strong negative weighting (i.e., >-1.5) are strongly evolved mineral soils with poorer drainage, high Clay% and low N% (Figure 3-8). Therefore, PC3 is indicative of soil drainage and leaching.

TC3.3.4 Principal Component 4 - Soils Ability to Bind Phosphorus

Principal Component 4 (PC4) explains 9.4% of the variance in the data set with the strongest positive weightings for Clay%, P-retention, and drainage class, and negative weights for C%, and C:N ratio. On the basis of these findings, PC4 can be used to explain the soils ability to bind P, which is strongly related to texture. The most positive weightings on well-developed mineral soils have high P-retention and the most negative weightings found in highly organic peat soils have low P-retention (Figure 3-9).

TC3.3.5 Principal Component 5 - controls over the exchangeable bases

Principal Component 5 (PC5) explains 8.7% of the variance in the data with strongest positive weightings for Clay% and available N, and smaller positive weightings for Ca, pH and P-retention. Strong negative weightings are evident for K, Mg, Na and drainage class. It is difficult to determine with high certainty what this component represents, however it is likely to be related to controls over the exchangeable bases. The most positive values are associated with Ca as the dominant cation, whilst the most negative values are related to Mg, K and Na (Figure 3-10).

In summary, PCA of Southland soil chemical data indicates that soil weathering, followed closely by parent material composition, are the two key drivers of soil chemical variation in Southland. Although these findings are not surprising, PCA is of high value as it provides an objective measure of the significance or magnitude of key soil forming factors over the natural chemical variation of Southland soils. Soil drainage and leaching (PC3) also emerge as key variables along with P-retention (PC4). In terms of the hydrochemistry of Southland’s waters it is important to note that both soil weathering (PC1) and parent materials (PC2) play a critical role in determining soil pH and BS%, and that both of these variables exert a major control over alkalinity, Total Dissolved Solids (TDS) concentration and major ion facies of soil water drainage (see TC 4).

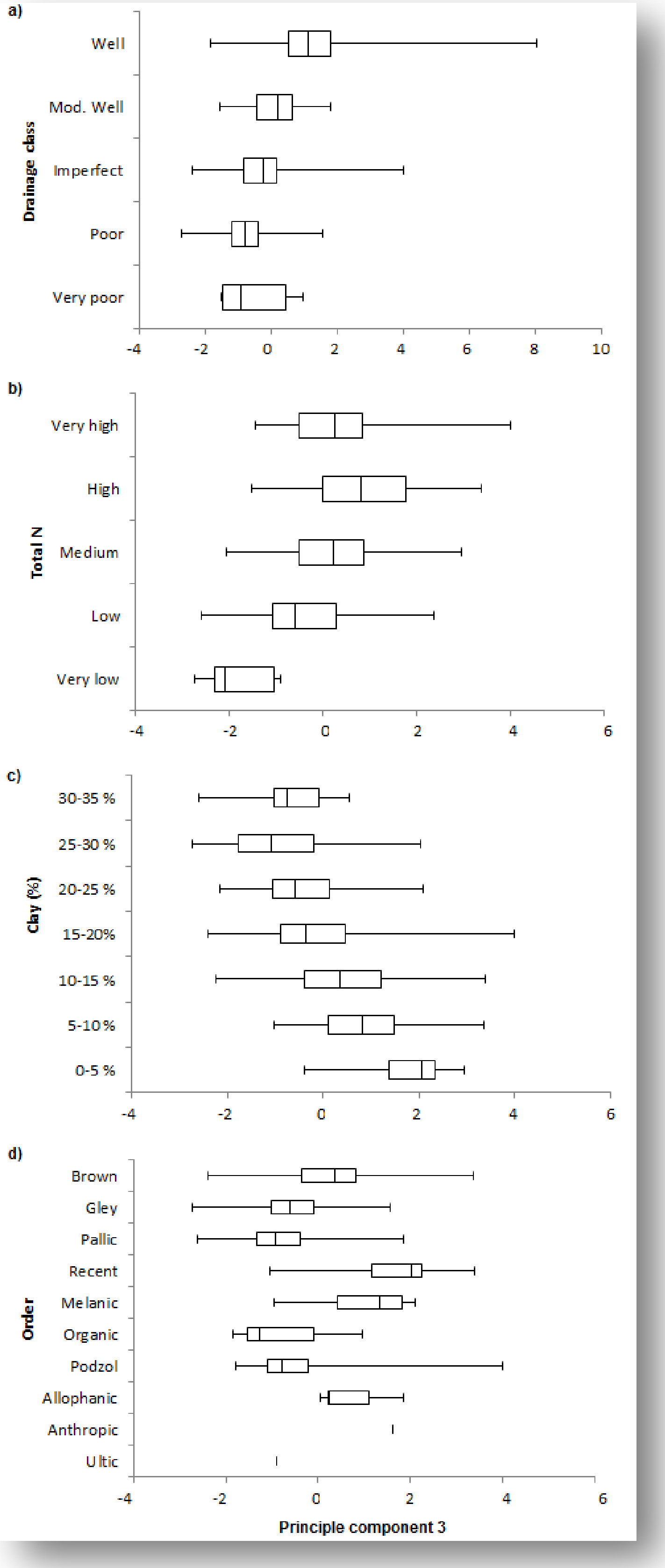

Figure 3-8: PC3 by a) drainage class, b) total nitrogen, c) clay percentage, and d) NZSC Order.

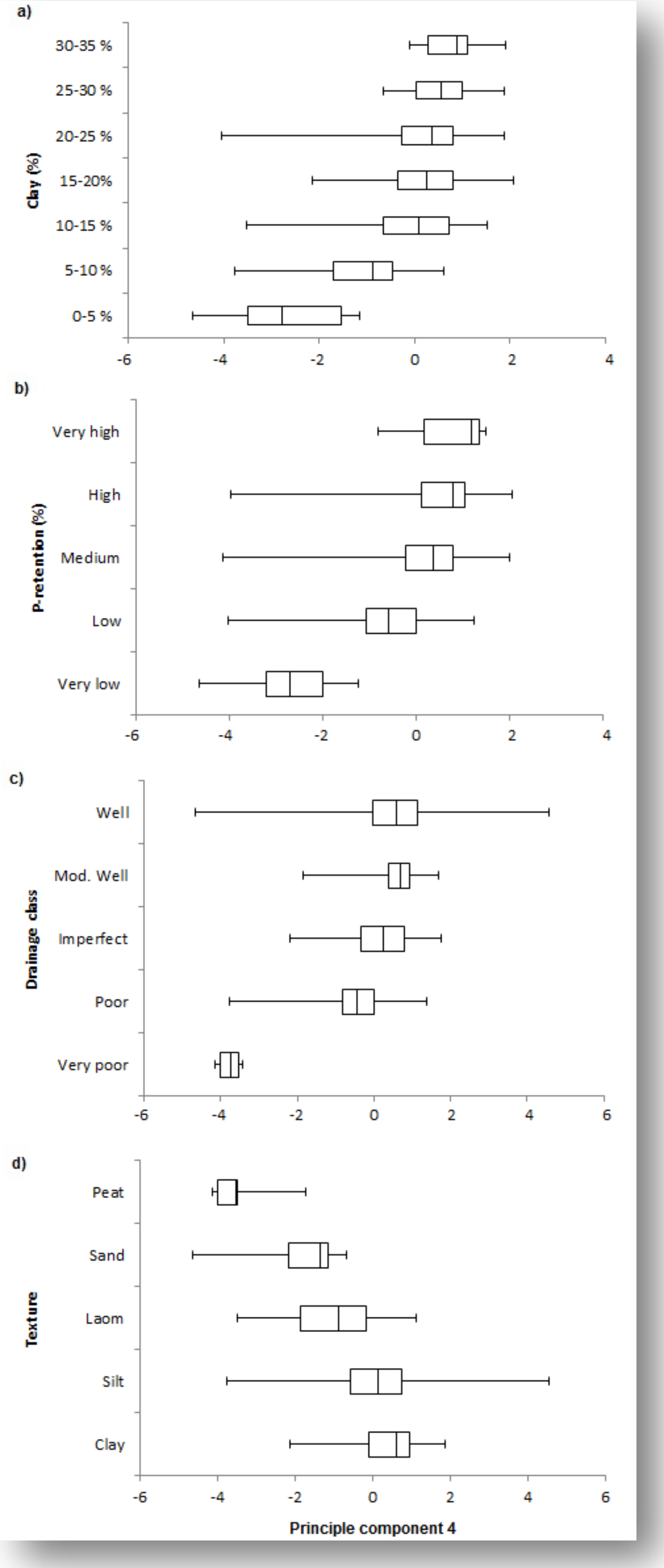

Figure 3-9: PC4 by a) clay %, b) P-retention, c) drainage class, and d) soil texture.

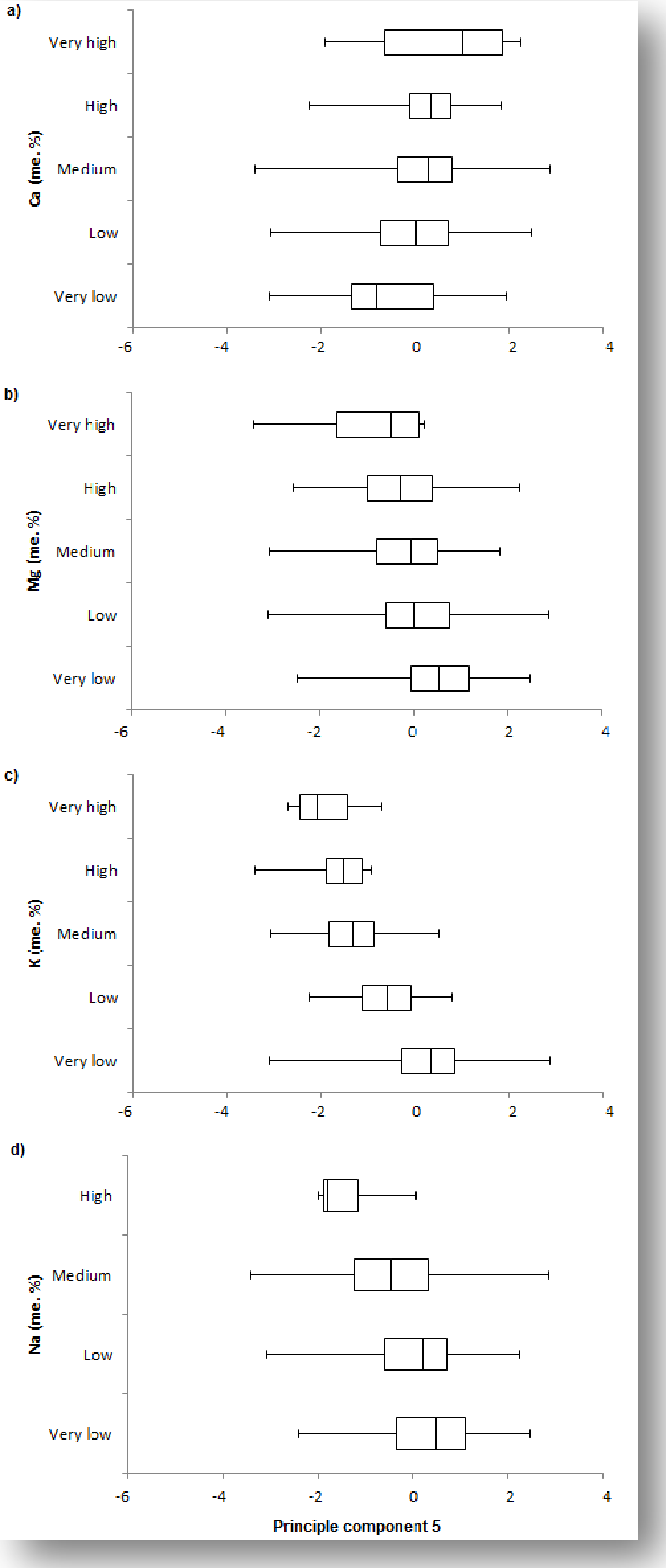

Figure 3-10: PC5 by exchangeable bases a) Calcium, b) Magnesium, c) Potassium, and d) Sodium.

TC3.4 Hierarchal Cluster Analysis of Southland’s Soil Chemical Data set

Hierarchal Cluster Analysis (HCA) was carried out to identify soils of similar chemical characteristics. HCA of Southland’s soil chemical data set was applied to log10 transformed, Z-scored data[3]. We identified that 3 and 6 at the 900 and 500 phenon lines were the optimal number of resolvable clusters using Bayesian Information Criterion and Ward hierarchical clustering methods.

TC3.4.1 900 Phenon line

At a high level (900 phenon line) Southland soil chemical data clusters into three distinct groups (Figure 3-11 and Table 3-5). Cluster 1a represents between 119 and 121 individual soil chemical profiles and comprises over 29% of the data. Cluster 1b is the largest grouping and represents between 221 and 222 individual soil profiles (54% of the data). The smallest group is cluster 2, which represents between 68 and 69 profiles and 17% of the data (Table 3-6). To assess the differences in chemical signature of the identified clusters, box plots of soil chemistry were established. These are illustrated in Figure 3-12 and Figure 3-13 and will be discussed further in the following.

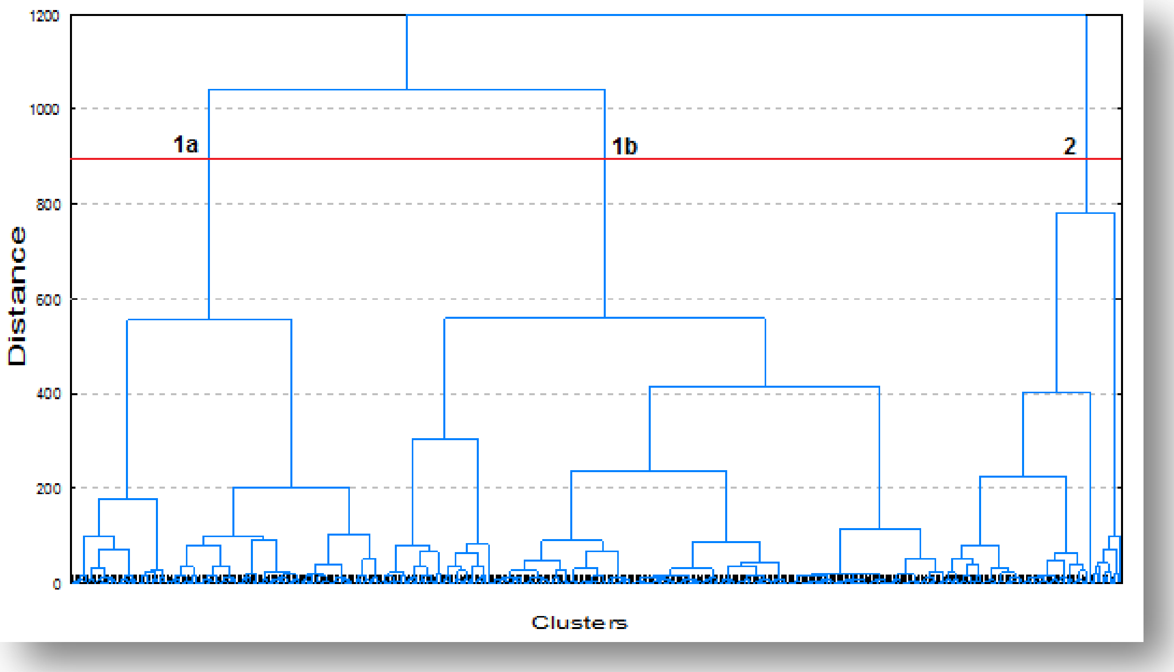

Figure 3-11: Dendrogram with 3 clusters identified at the 900 phenon line (red) (Measure: Squared Euclid, Method: Ward).

Table 3-5: Clusters identified at the 900 phenon line.

Cluster number	Cluster Name	Cases	Percentage
1	1a	121	29.4%
2	1b	222	53.9%
3	2	69	16.8%

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[3] There was no need to log10 transform pH.

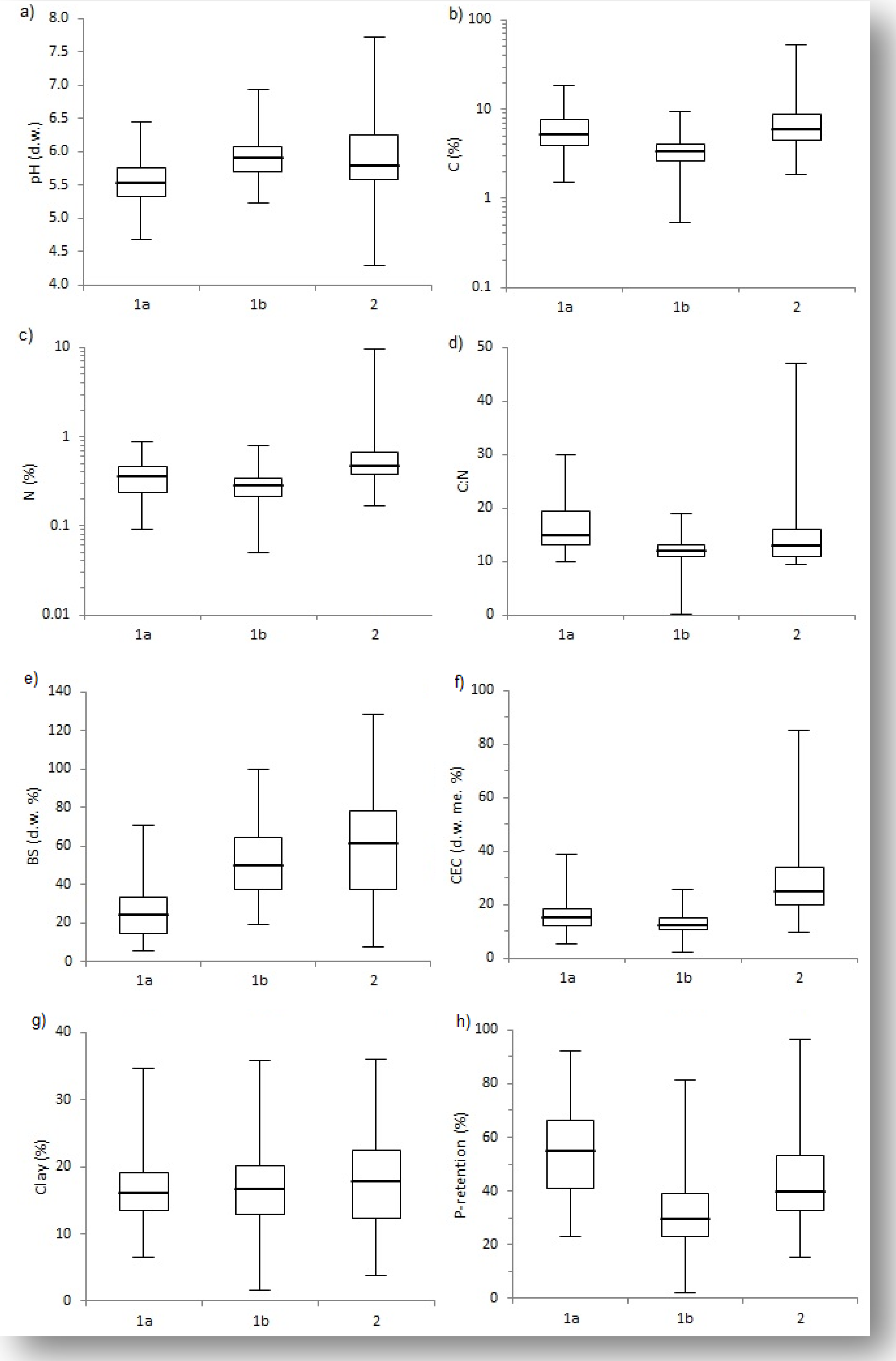

Figure 3-12: HCA at (900 phenon line) showing a) pH, b) carbon (%), c) nitrogen (%), d) C:N ratio, e) base saturation (%), f) cation exchange capacity, g) clay (%), and h) P-retention (%). Note the log scale for b) carbon, and c) nitrogen.

Table 3-6: Summary statistics of soil chemistry by soil cluster at the 900 phenon line.

Cluster 1a	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	121	121	121	121	121	121	121	121	121	121	121	121	121	119
Mean	5.5	25.5	16.0	3.1	0.9	0.2	0.2	5.9	0.4	16.5	54.2	16.4	3.4	0.4
Median	5.5	24.1	15.2	2.5	0.5	0.2	0.2	5.2	0.4	15.0	55.0	16.2	3.0	0.4
Standard Deviation	0.3	13.2	6.1	2.3	0.9	0.2	0.2	3.0	0.2	4.8	15.1	4.7	1.2	0.3
Coefficient of Variation	0.1	0.5	0.4	0.7	1.0	0.9	0.8	0.5	0.4	0.3	0.3	0.3	0.3	0.6
Minimum	4.7	5.3	5.3	0.2	0.1	0.0	0.0	1.5	0.1	10.0	23.3	6.5	2.0	0.0
Maximum	6.4	70.7	39.1	14.2	3.7	1.7	1.0	18.4	0.9	30.0	92.0	34.7	5.0	1.3
Range	1.8	65.4	33.8	14.0	3.7	1.7	1.0	16.9	0.8	20.0	68.8	28.2	3.0	1.2

Cluster 1b	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	222	222	222	222	222	222	222	222	222	222	222	222	222	221
Mean	5.9	51.9	12.8	5.3	1.2	0.2	0.2	3.4	0.3	12.1	33.2	16.6	3.3	0.4
Median	5.9	49.9	12.5	5.1	0.8	0.1	0.1	3.4	0.3	12.0	29.4	16.7	3.0	0.3
Standard Deviation	0.3	18.0	3.9	2.2	1.0	0.2	0.1	1.3	0.1	2.0	15.5	6.5	1.2	0.2
Coefficient of Variation	0.0	0.3	0.3	0.4	0.9	1.2	0.5	0.4	0.4	0.2	0.5	0.4	0.4	0.6
Minimum	5.2	19.0	2.1	0.8	0.1	0.0	0.0	0.5	0.1	0.1	2.0	1.6	2.0	0.0
Maximum	6.9	99.9	25.9	13.6	7.0	1.8	0.7	9.5	0.8	19.0	81.4	35.8	5.0	0.9
Range	1.7	80.9	23.8	12.8	6.9	1.7	0.7	9.0	0.8	18.9	79.4	34.2	3.0	0.9

Cluster 2	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	68	68	68	68	68	68	68	68	68	68	68	68	69	69
Mean	5.8	59.9	29.2	12.1	3.1	0.5	0.3	10.9	0.7	15.5	44.7	17.7	3.3	0.5
Median	5.8	61.5	25.1	11.1	2.7	0.3	0.3	5.9	0.5	13.0	39.6	17.9	3.0	0.4
Standard Deviation	0.7	26.9	15.0	7.5	1.9	0.6	0.2	12.6	1.2	7.8	18.3	7.2	1.5	0.3
Coefficient of Variation	0.1	0.4	0.5	0.6	0.6	1.2	0.7	1.1	1.6	0.5	0.4	0.4	0.5	0.7
Minimum	4.3	7.7	9.5	2.7	0.4	0.1	0.0	1.8	0.2	9.5	15.2	3.8	1.0	0.0
Maximum	7.7	128.5	85.1	44.8	9.4	2.9	1.4	52.9	9.7	47.0	96.4	36.0	5.0	1.2
Range	3.4	120.8	75.6	42.1	9.0	2.8	1.3	51.0	9.5	37.5	81.2	32.2	4.0	1.1

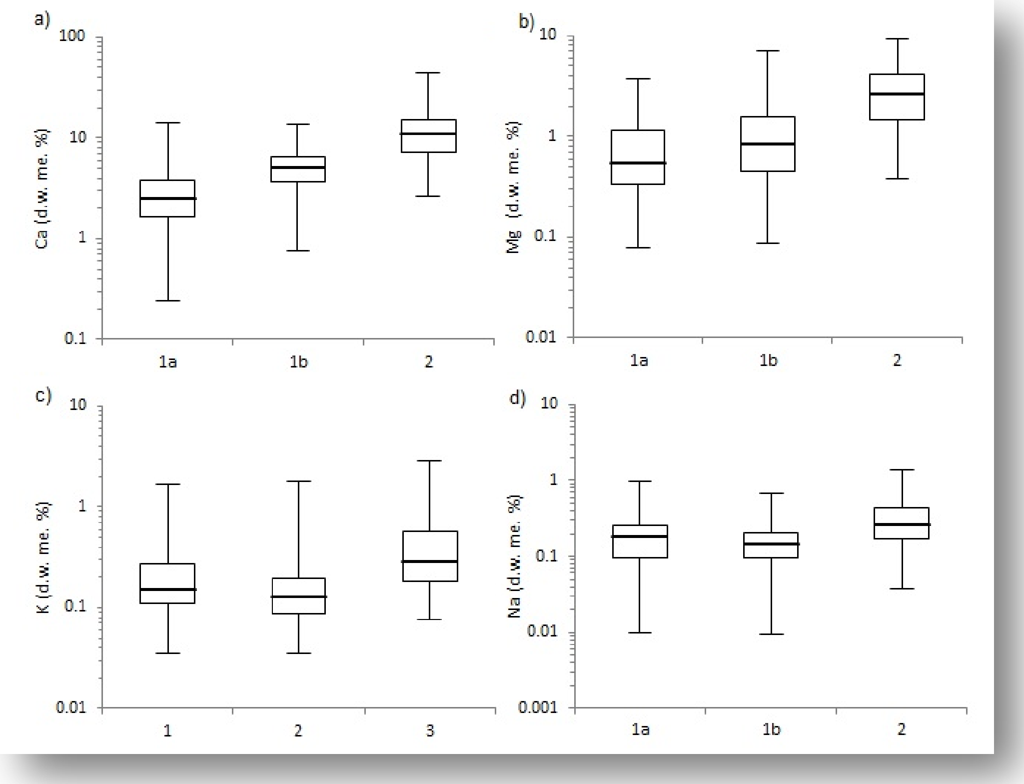

Figure 3-13: HCA at (900 phenon line) showing major exchangeable bases a) calcium (meq%), b) magnesium (meq%), c) potassium, and d) sodium (meq%).

At a pedogenic level, NZSC Orders within the three clusters are highly varied. In Cluster 1a, the majority of the soil profiles are Brown soils, lesser Gley soils and even fewer Podzol, Pallic, and Allophanic soils (Figure 3-14). Cluster 1a soils are found predominantly on the southern plains and in the Te Anau basin where Brown soils are most common (Figure 3-15). In Cluster 1b, the majority soil profiles occur as Brown soils and Pallic, Gley, Recent and Melanic soils. Cluster 1b soils are widespread across the Southland region, occurring where Pallic and Gley soils are most common. Cluster 2 is predominantly Gley and Brown soils and fewer Pallic, Organic, Melanic soils. Cluster 2 soils are located primarily near wetlands or areas of high available water (Figure 3-14, Figure 3-15).

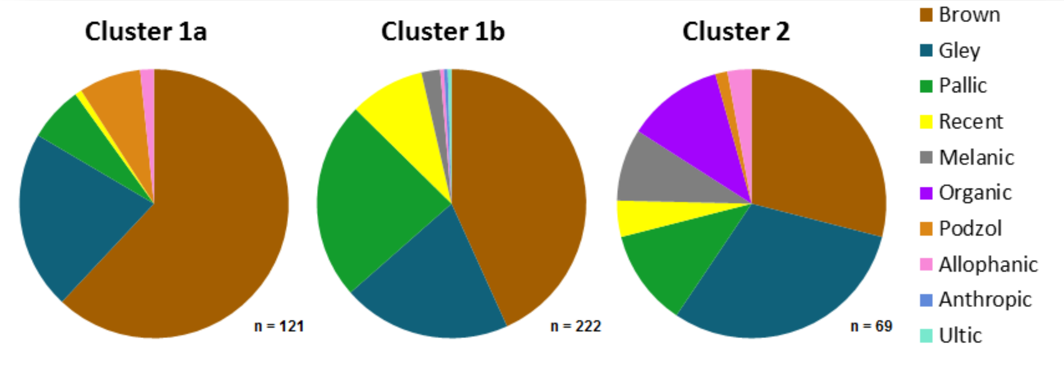

Figure 3-14: HCA (900 phenon line) by NZSC Order.

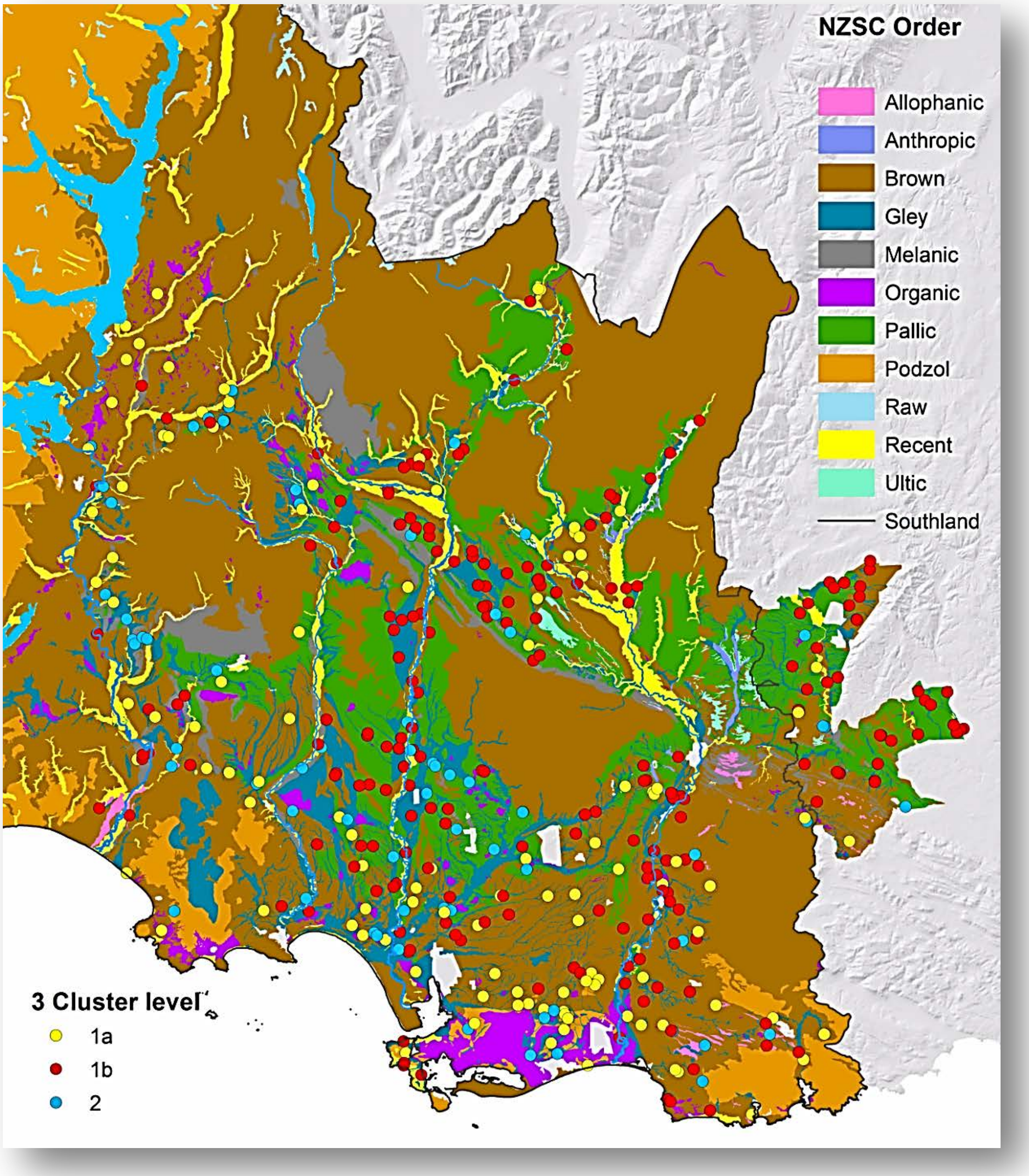

Figure 3-15: HCA (900 phenon line) by NZSC Order spatially. Note some points within the Topoclimate South soil survey are in the Otago region. The line represents the Southland regional boundary.

Cluster 1a

At this relatively high clustering level, the defining chemical characteristics of the soils are a lower median base saturation (24%) as well as concentrations of Ca and Mg. Cluster 1a soils have the lowest median pH (5.5) when compared to Cluster 1b and 2 soils (Figure 3-12 and Figure 3-13). Soil C% and N% are slightly higher than Cluster 1b. CEC is moderate (15%), falling between Cluster 1b (12.4%) and Cluster 2 (25%). The chemical signatures of Cluster 1a soils are consistent with moderately to well-developed mineral soils (Figure 3-16).

At a pedogenic level, NZSC orders and groups within Cluster 1a are highly varied, although 62% of the 121 individual soil profiles are Firm, Orthic and Allophanic Brown soils (Figure 3-14). The remaining soil orders within Cluster 1a comprise mainly Orthic and Gley soils. The main subgroup designations (n>10) for Cluster 1a soils are Acidic > Typic > Mottled > Mafic. Although varied, the pedogenic characteristics of the aforementioned soils are consistent with a chemical interpretation of relatively evolved/pedogenically differentiated mineral soils of moderate to low BS% and pH in association with older, relatively stable landform units (Figure 3-15). Cluster 1a soils are prominent within the Te Anau Basin, lowland coastal areas of Southland and areas where old stable landforms are formed in felsic parent materials including granite and/or quartz. There is an apparent association with the old Q8 – Q10 Kamahi and Waikiwi Terrace Formations of south-eastern Southland and coastal marine terraces.

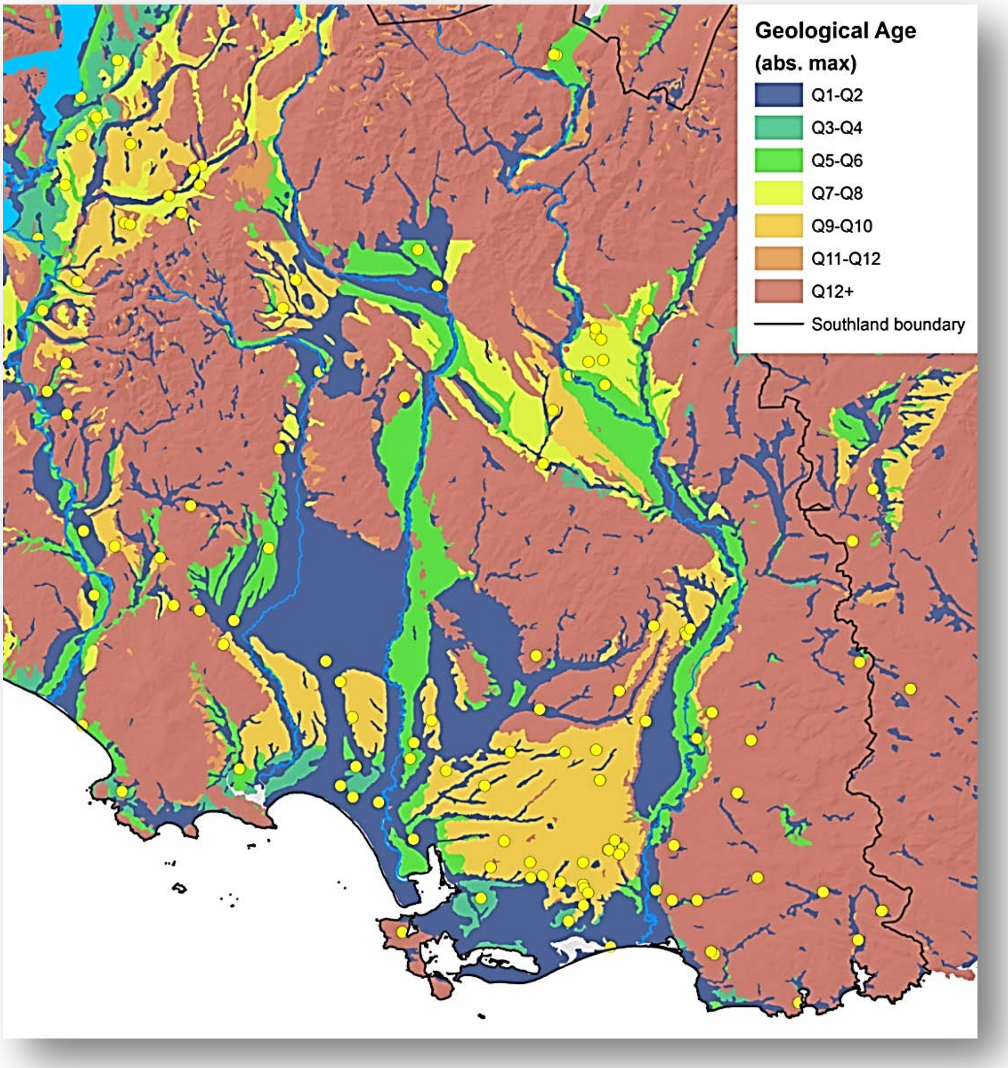

Figure 3-16: Cluster 1a (yellow) distribution with geological age from Qmap (Heron, 2014).

Drainage class is not significant at this high clustering level as Cluster 1a soils have similar proportions of poorly-, moderate- and well- drained soils. Well- to moderately-well- drained soils comprise 43% of Cluster 1a with imperfectly- (30%) and poorly- drained soils (27%). We note that although there are some questions surrounding the resolution of soil drainage class assignments relative to site specific soil chemical data (i.e., they are generalised interpretations associated for type profiles and not specific to the site for which soil chemical data was taken) assessment of drainage class provides a generalised summary for each cluster.

Cluster 1b

Cluster 1b is the largest group and distinguished from 1a by higher pH values, lower C%, N%, CEC, and higher BS%, Ca, and Mg concentrations (Figure 3-12, Figure 3-13). CEC is low due to both low C% and Clay%. Median P-retention for Cluster 1b soils is low (29%) relative to Clusters 1a and 2. These chemical signatures are consistent with Recent soils or soils subject to poor drainage and limited leaching. Cluster 1b soils are found on younger to intermediate landforms, along or immediately adjacent to recent floodplains or active stream channels of main stem and higher order stream and river systems across Southland (Figure 3-17).

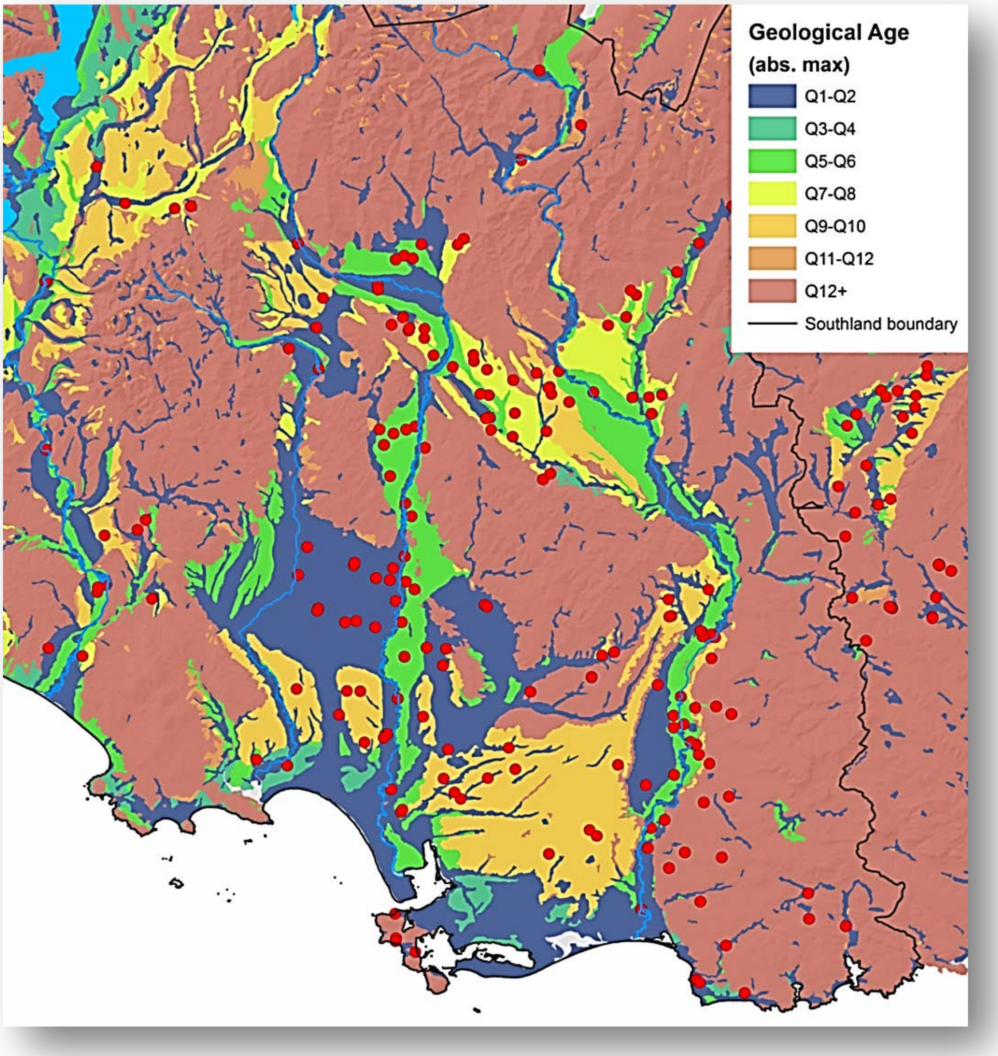

Figure 3-17: Cluster 1b (red) distribution with geological age from Qmap (Heron, 2014).

At a pedogenic level, the NZSC order and group classifications for Cluster 1b are predominantly Firm, Orthic and Brown soils (Figure 3-14). The main subgroup designations (n>10) for Cluster 1b soils are Typic > Mottled > Pallic > Acidic > Fragic > Argillic-Fragic. Poorly- and imperfectly- drained soils account for 59% of these soils with the remainder being well- and moderately-well- drained soils. Spatially, Cluster 1b soils are associated with young (Q1 - Q2) and intermediate age (Q6 and up to Q8 – Q10) stable alluvial surfaces. These soils are predominantly fine textured silt, loam soils derived from wind-blown loess or alluvial deposits.

Cluster 2

The soils of Cluster 2 are distinguished from Clusters 1a and 1b by high C%, N% and exchangeable bases (Ca, Mg, K and Na). pH covers the largest range with the most acidic and most alkaline soils in this cluster. Mean BS% and CEC is also highest in this cluster. P-retention is medium (40%) compared to the other clusters.

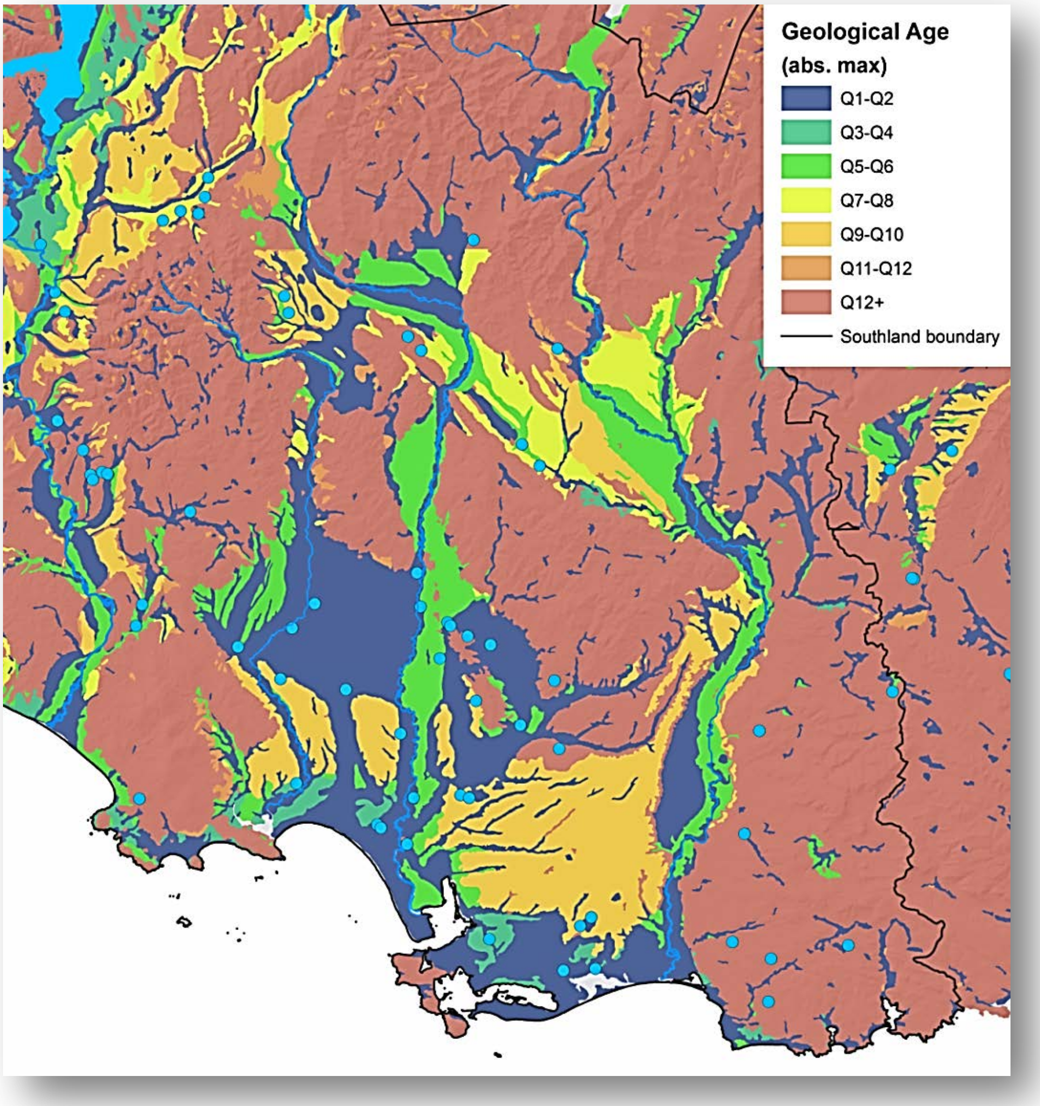

Figure 3-18: Cluster 2 (blue) distribution with geological age from Qmap (Heron, 2014).

At a pedogenic level the NZSC orders and groups for Cluster 2 are predominantly Orthic Gley and Orthic Brown soils. The majority of the remaining 41% of the soil profiles occur as Humic Organic and Perch-gley, Immature and Argillic Pallics, and Fluvial Recent soil. The main subgroup designations (n>5) for Cluster 2 soils are Typic > Acidic > Argillic. These signatures all suggest highly weathered soils with high accumulations of organic carbon and organic soils (Figure 3-18).

Geomorphically, Cluster 2 soils show a strong association with low-lying low order stream channels or old (Q8 and older) highly weathered landforms of coastal Southland. Type locations include the lower half of the Waituna Catchment, the low-lying, modern day floodplains of the Kamahi Formation and the most coastal occurrences of Southland hill country (e.g. coastal regions of the Longwoods and Catlins Ranges, Figure 3-18). Poorly-, very poorly- and imperfectly- drained soils account for 55% of these soils with the other 45% being well- and moderately-well- drained soils.

TC3.4.2 500 Phenon line

At a finer level (500 phenon line) Clusters 1a, 1b, and 2 are differentiated into six smaller distinct clusters (Table 3-7, Figure 3-19). Each 900 phenon line cluster is divided into two sub-groups at the 500 phenon line. Cluster 1a is split into two smaller clusters designated as 1a1 and 1a2, as with Cluster 1b which is divided into 1b1 and 1b2 and Cluster 2 is divided into clusters 2a and 2b (Table 3-8) . Box plots of chemical data by cluster are shown in Figure 3-20 and Figure 3-21 and will be discussed further in the following Technical Chapter.

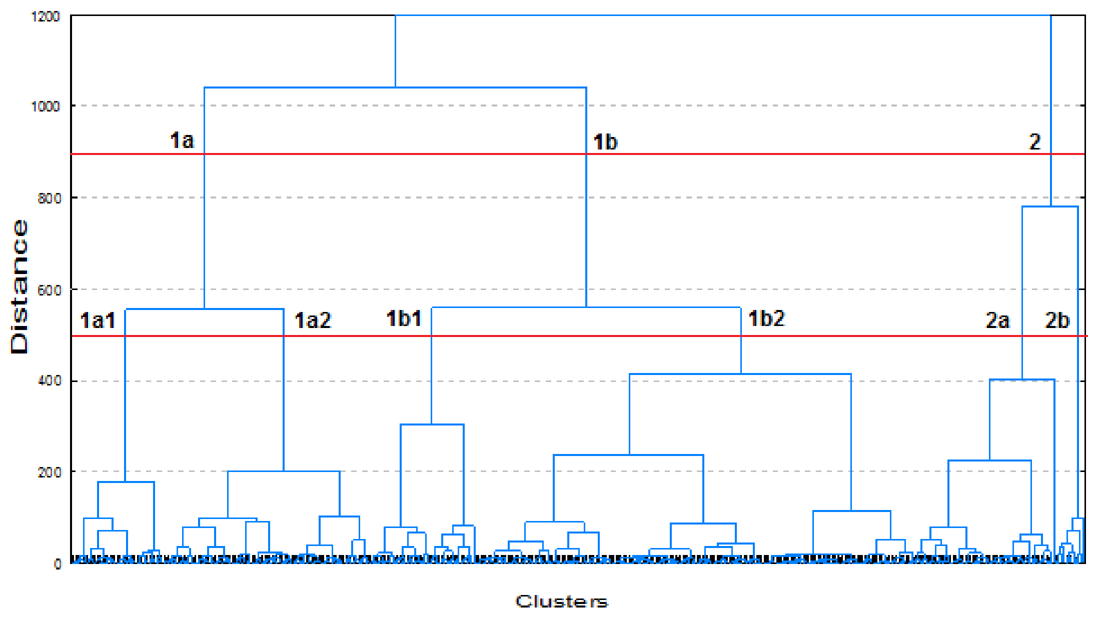

Figure 3-19: Dendrogram with 6 clusters at the 500 phenon line (red) (Measure: Squared Euclid, Method: Ward).

Table 3-7: Clusters identified at the 500 phenon line.

Cluster	Name	Cases	Percentage
1	1a1	37	8.9%
2	1a2	84	20.4%
3	1b1	43	10.4%
4	1b2	179	43.5%
5	2a	57	13.8%
6	2b	12	2.9%

Table 3-8: Summary statistics of soil chemistry by soil cluster at the 500 phenon line.

Cluster 1a1	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	37	37	37	37	37	37	37	37	37	37	37	37	37	35
Mean	5.7	16.5	11.6	1.7	0.3	0.1	0.1	4.8	0.3	15.6	56.1	12.9	4.7	0.2
Median	5.7	13.5	11.0	1.3	0.3	0.1	0.1	4.8	0.3	14.0	55.5	13.0	5.0	0.1
Standard Deviation	0.3	10.3	2.7	1.5	0.2	0.1	0.1	1.9	0.1	4.3	12.8	3.8	0.6	0.1
Coefficient of Variation	0.1	0.6	0.2	0.9	0.6	0.8	0.8	0.4	0.4	0.3	0.2	0.3	0.1	0.5
Minimum	5.2	5.3	5.3	0.2	0.1	0.0	0.0	1.7	0.1	11.0	26.7	6.5	3.0	0.0
Maximum	6.4	49.8	18.2	6.4	0.7	0.6	0.4	10.9	0.7	26.3	79.5	20.2	5.0	0.4
Range	1.3	44.5	12.9	6.2	0.6	0.5	0.4	9.2	0.6	15.3	52.8	13.7	2.0	0.4

Cluster 1a2	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	84	84	84	84	84	84	84	84	84	84	84	84	84	84
Mean	5.5	29.4	18.0	3.7	1.2	0.3	0.2	6.4	0.4	16.8	53.4	17.9	2.9	0.5
Median	5.5	27.2	16.7	3.0	0.9	0.2	0.2	5.7	0.4	15.2	55.0	17.6	3.0	0.5
Standard Deviation	0.3	12.4	6.2	2.3	1.0	0.2	0.2	3.3	0.2	4.9	16.0	4.3	0.9	0.3
Coefficient of Variation	0.1	0.4	0.3	0.6	0.8	0.9	0.7	0.5	0.4	0.3	0.3	0.2	0.3	0.5
Minimum	4.7	9.0	8.3	0.6	0.1	0.1	0.0	1.5	0.1	10.0	23.3	9.0	2.0	0.1
Maximum	6.1	70.7	39.1	14.2	3.7	1.7	1.0	18.4	0.9	30.0	92.0	34.7	5.0	1.3
Range	1.4	61.6	30.7	13.6	3.6	1.6	1.0	16.9	0.8	20.0	68.8	25.7	3.0	1.2

Cluster 1b1	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	43	43	43	43	43	43	43	43	43	43	43	43	43	42
Mean	6.1	61.0	10.6	5.2	1.0	0.4	0.1	3.2	0.3	12.1	20.5	9.2	4.5	0.2
Median	6.2	59.4	9.7	4.4	0.7	0.2	0.1	3.2	0.3	12.0	20.3	8.8	5.0	0.1
Standard Deviation	0.3	18.9	5.4	3.0	1.2	0.4	0.1	1.7	0.1	1.7	9.2	5.1	0.8	0.1
Coefficient of Variation	0.1	0.3	0.5	0.6	1.1	1.1	0.9	0.5	0.5	0.1	0.5	0.6	0.2	0.8
Minimum	5.5	21.8	2.1	0.8	0.1	0.0	0.0	0.5	0.1	9.0	2.0	1.6	2.0	0.0
Maximum	6.9	99.9	25.9	13.6	7.0	1.8	0.7	9.5	0.8	18.0	40.2	23.8	5.0	0.7
Range	1.4	78.1	23.8	12.8	6.9	1.7	0.7	9.0	0.8	9.0	38.2	22.2	3.0	0.7

Cluster 1b2	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	179	179	179	179	179	179	179	179	179	179	179	179	179	179
Mean	5.9	49.7	13.3	5.3	1.2	0.2	0.2	3.4	0.3	12.1	36.3	18.4	3.0	0.4
Median	5.9	48.1	12.9	5.1	0.9	0.1	0.2	3.4	0.3	12.0	32.5	17.8	3.0	0.4
Standard Deviation	0.2	17.1	3.3	2.0	1.0	0.1	0.1	1.1	0.1	2.1	15.1	5.5	1.1	0.2
Coefficient of Variation	0.0	0.3	0.3	0.4	0.8	0.7	0.4	0.3	0.3	0.2	0.4	0.3	0.4	0.5
Minimum	5.2	19.0	6.3	1.4	0.1	0.0	0.0	1.0	0.1	0.1	13.1	6.3	2.0	0.1
Maximum	6.5	97.9	24.1	11.9	4.6	0.7	0.4	7.8	0.6	19.0	81.4	35.8	5.0	0.9
Range	1.3	78.9	17.8	10.5	4.5	0.7	0.4	6.7	0.5	18.9	68.3	29.6	3.0	0.9

Cluster 2a	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	56	56	56	56	56	56	56	56	56	56	56	56	57	57
Mean	6.1	67.1	25.4	12.9	3.2	0.5	0.3	5.7	0.5	12.5	44.9	19.0	3.6	0.4
Median	6.0	67.9	24.0	12.0	2.7	0.3	0.3	5.5	0.4	12.0	39.6	19.3	4.0	0.3
Standard Deviation	0.5	23.6	8.6	7.6	2.0	0.6	0.2	2.2	0.2	2.2	18.4	6.7	1.4	0.3
Coefficient of Variation	0.1	0.4	0.3	0.6	0.6	1.2	0.5	0.4	0.4	0.2	0.4	0.4	0.4	0.7
Minimum	5.4	27.4	9.5	3.2	0.4	0.1	0.0	1.8	0.2	9.5	16.0	6.3	2.0	0.0
Maximum	7.7	128.5	46.0	44.8	9.4	2.9	0.7	12.1	0.9	20.0	96.4	36.0	5.0	1.0
Range	2.4	101.1	36.4	41.6	9.0	2.8	0.7	10.2	0.8	10.5	80.4	29.8	3.0	1.0

Cluster 2b	pH (d.w.)	BS (d.w. %)	CEC (d.w. %)	Ca (d.w. %)	Mg (d.w. %)	K (d.w. %)	Na (d.w. %)	C (%)	N (%)	C:N	P-ret. (%)	Clay (%)	Drainage	SDNP
Valid Cases	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Mean	4.7	25.9	46.9	8.6	2.7	0.4	0.5	35.5	1.9	29.5	43.7	11.6	1.8	0.8
Median	4.6	29.1	41.1	6.0	2.8	0.2	0.3	35.4	1.3	30.0	43.4	11.5	1.5	0.9
Standard Deviation	0.3	10.3	24.3	6.3	1.5	0.4	0.4	11.8	2.5	9.3	18.5	6.5	1.2	0.2
Coefficient of Variation	0.1	0.4	0.5	0.7	0.6	1.1	0.8	0.3	1.3	0.3	0.4	0.6	0.7	0.2
Minimum	4.3	7.7	15.0	2.7	0.9	0.1	0.1	16.3	0.5	13.0	15.2	3.8	1.0	0.4
Maximum	5.2	37.4	85.1	21.2	5.4	1.5	1.4	52.9	9.7	47.0	71.0	23.3	5.0	1.2
Range	1.0	29.7	70.1	18.6	4.6	1.4	1.3	36.6	9.2	34.0	55.8	19.5	4.0	0.7

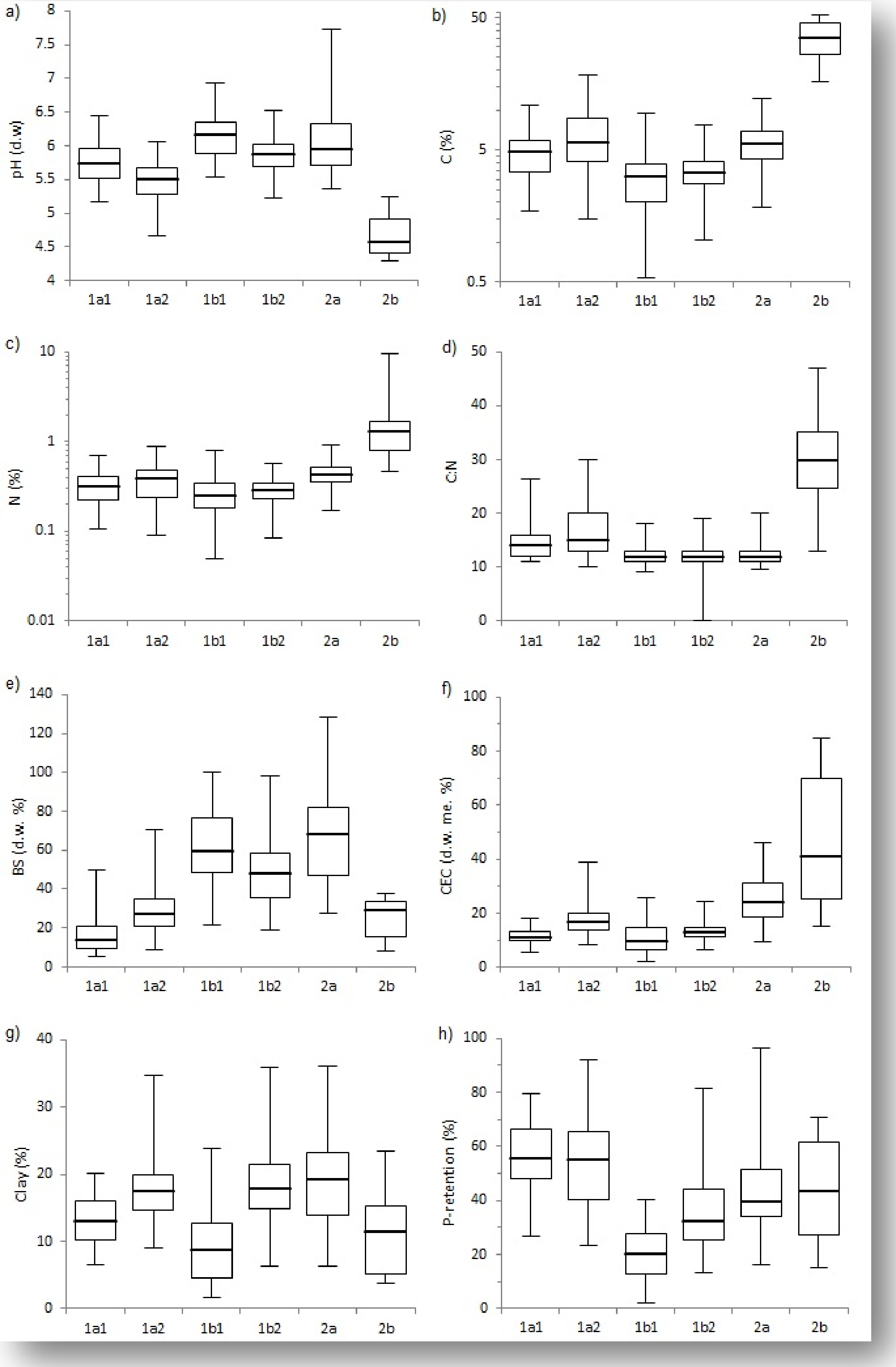

Figure 3-20: HCA at (500 phenon line) showing a) pH, b) carbon (%), c) nitrogen (%), d) C:N ratio, e) base saturation (%), f) cation exchange capacity (meq%), g) clay (%), and h) P-retention (%).

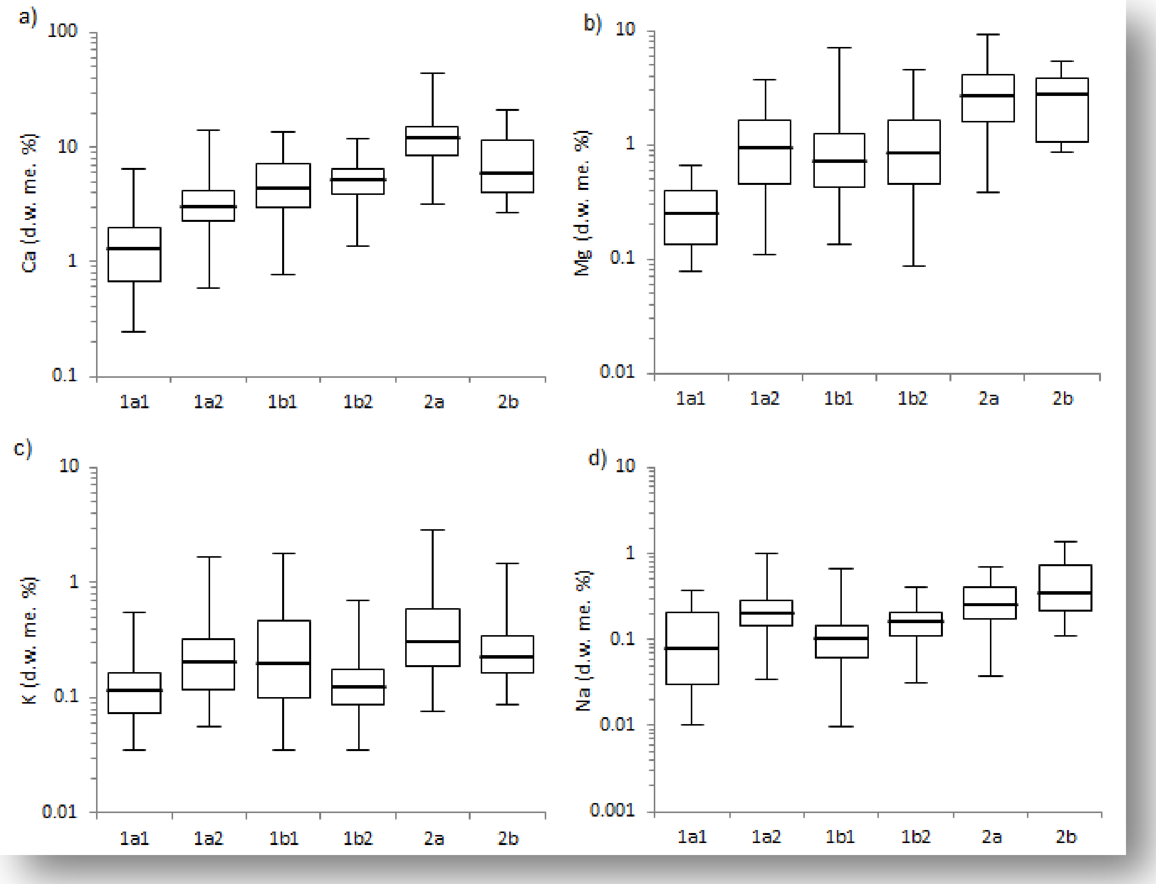

Figure 3-21: HCA at (500 phenon line) showing major exchangeable bases a) calcium (meq%), b) magnesium (meq%), c) sodium (meq%), and d) potassium (meq%). Note the log scale.

At a pedogenic level, Cluster 1a1 soils are dominantly Brown soils (91%) with one individual Pallic, Recent and Allophanic soil profile, whilst 1a2 soils are 49% Brown and Gley (31%) with minor Podzol (11%) and Pallic (8%) soils (Figure 3-22). Cluster 1b is split into clusters 1b1, which is predominantly Recent (46.5%), Brown (32.5%) and Pallic (12%) soils with minor Melanic (4.6%), and an individual Gley and Anthropic profile; and 1b2, which is made up of Brown (46%), Pallic (27%) and Gley (24.5%) soils with minor Melanic (1.6%) and an individual Allophanic and Ultic soil profile (Figure 3-22). Cluster 2 soils are split into 2a and 2b. Cluster 2a is predominantly made up of Brown (34%), Gley (32%), Pallic (14%) and Melanic (11%) soils with minor Recent (5%) and Allophanic (3.5%) soils; while Cluster 2b is dominated by Organic (67%), Gley (25%) and minor Podzol soils (8%) (Figure 3-22).

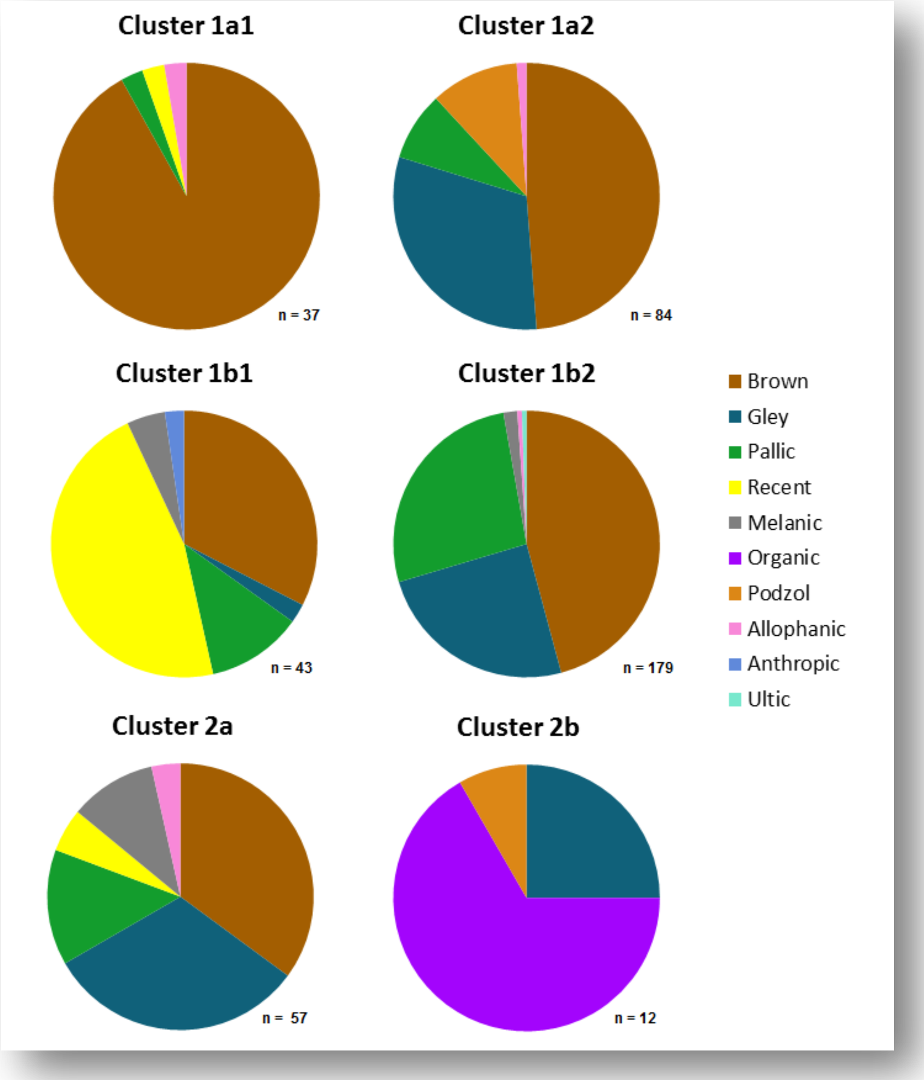

Figure 3-22: HCA (500 phenon line) by soil order.

Cluster 1a1

Cluster 1a1 represents acidic soils of low BS% and moderate C% and N% (Figure 3-20). Cluster 1a1 soils have low CEC and BS% and correspondingly the lowest concentrations of exchangeable Ca, Mg, K and Na of all clusters (Figure 3-20, Figure 3-21). P-retention is high, consistent with greater Al and Fe oxide/oxyhydroxide development and also suggests a significant proportion of the Clay% occurs as Allophane. Spatially, Cluster 1a1 soils occur predominantly within the Te Anau Basin in association with glacial till and glacial outwash surfaces formed in felsic parent materials. A few occurrences of Cluster 1a1 soils are associated with felsic, loess mantled surfaces in Southland, including lowland alluvial outwash formations and hill country (Figure 3-23).

At a pedogenic level, Cluster 1a1 soils are dominantly Brown soils (91%) with one individual Pallic, Recent and Allophanic soil profile each (Figure 3-22). Brown soils (n=34) include Firm (n=20), Orthic (n=8), and Allophanic (n=6) at the group level. At the Sub-group level the Brown soils are Typic (n=10) and Cemented (n=9) with minor Pallic, Acidic and Fill. The other soils that make up this cluster are a Typic Laminar Pallic (n=1), Typic Fluvial Recent (n=1) and a Typic Orthic Allophanic (n=1) soil. This cluster is comprised of well- to moderately-well- drained (90%) soils on rolling or undulating older terrains.

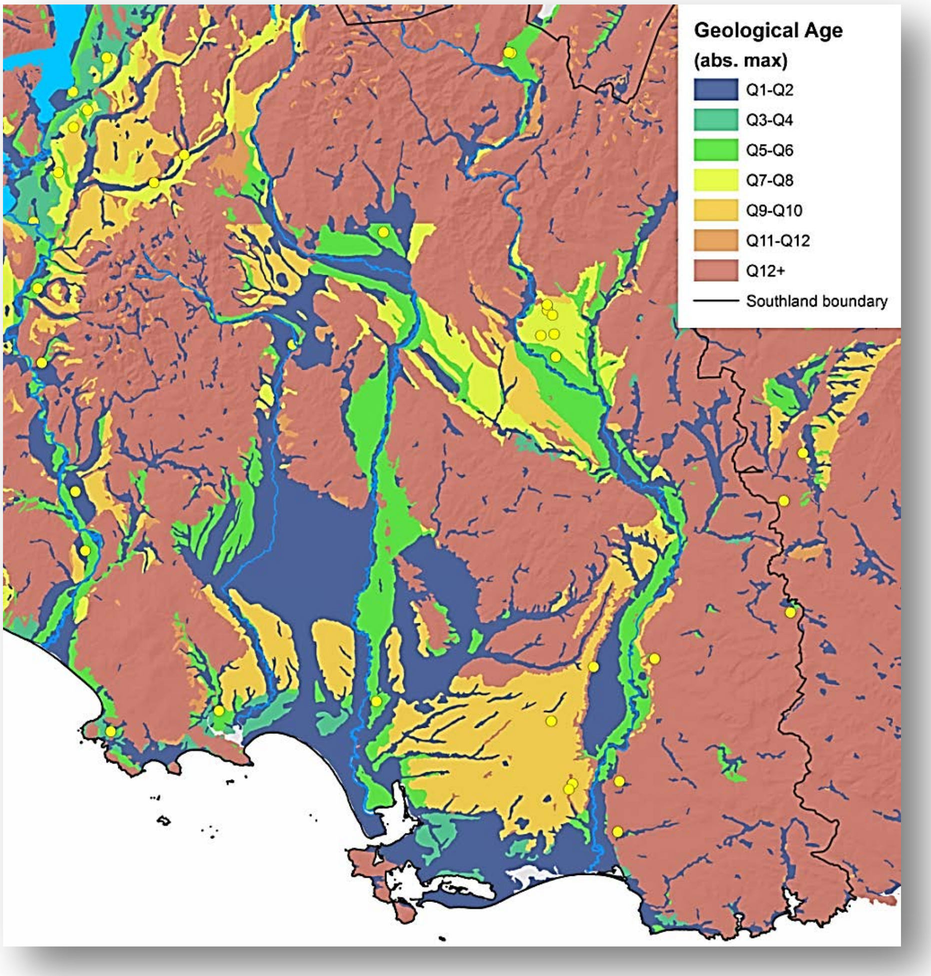

Figure 3-23: Cluster 1a1 distribution with geological age from Qmap (Heron, 2014).

Cluster 1a2

Relative to other clusters, Cluster 1a2 soils are distinguished by higher exchangeable Ca, M, K and Na compared to group 1a1 (Figure 3-21). C% and N% are also elevated compared to 1a1, resulting in higher BS% and CEC (Figure 3-20). Spatially, Cluster 1a2 soils are associated with stable alluvial surfaces of young (Q1al-Q2al) and intermediate age (Q6 and up to Q8-Q10). These soils are overwhelmingly fine textured, silt, loam soils with low C% derived from loess (Schmidt et al., 2005). All have slow permeability (<4 mm/hr) and aeration is moderate to severely limited. With the exception of low altitude and gentle sloping hills of south eastern Catlins, this Cluster is not associated with hill or high country bedrock (Figure 3-24).

At a pedogenic level, Cluster 1a2 soils are Brown (49%) > Gley (31%) > Podzol (10.7%) > and Pallic (8.3%) soils (Figure 3-22). Brown soils (n=41) include Firm (n=19), Orthic (n=15), Allophanic (n=5) and Acidic (n=2) at the group level with a predominance of Cemented (n= 9), Typic (n=7) and Pallic (n=6) designations at the Subgroup level. Gley soils are Orthic (n=20), Recent (n=5) and Acidic (n=1) at the group level and are predominantly Acidic and Typic at the Sub-group level. Podzol soils (n= 9) are predominantly Pan (n=7) with lesser Orthic (n=2) designations at the Subgroup level. Pallic soils (n=7) are all Perch-gley at the group level and Fragic, Argillic, Argillic-Fragic, and Typic at the sub-group level. Imperfectly- and poorly- drained soils are associated with 79% of the soils within this cluster occurring mainly as Gley and Mottled/Mottled-acidic Brown soils. The remaining 21% of soils are classified as moderately- to well- drained soils with Orthic, Firm and Allophanic Brown soils being classified as well-drained.

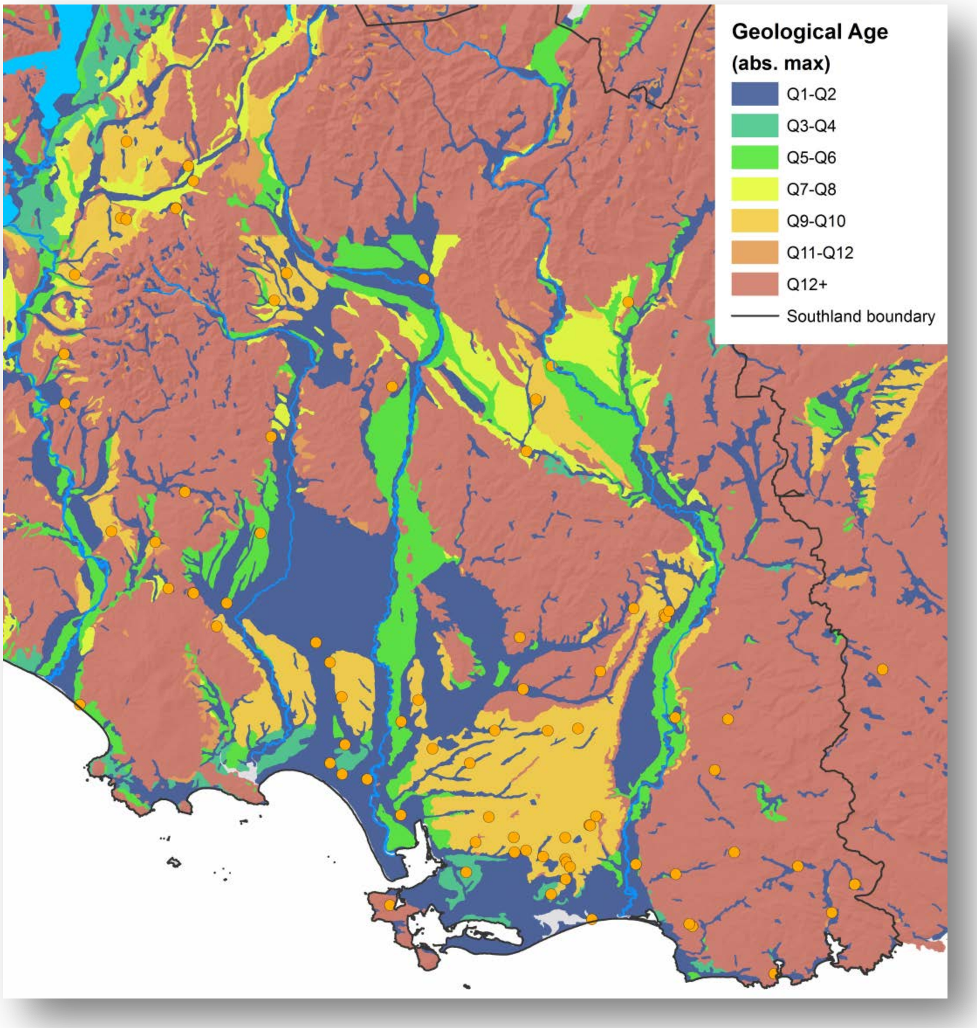

Figure 3-24: Cluster 1a2 distribution with geological age from Qmap (Heron, 2014).

Cluster 1b1

The soils of Cluster 1b1 are distinguished by the lowest median C%, N% and CEC (9.7%) (Figure 3-20, Figure 3-21). This cluster has the highest proportion of coarse textured gravel soils with the lowest Clay% (median 8.8%) of all the six clusters. Concentrations of Ca and Mg fall between the higher median value of Cluster 2 and the lower values of Cluster 1a. BS% is high (59.3%) and pH values the most elevated (median of 6.1) of the six clusters. However, CEC is low due to both low C% and Clay% and P-retention is very low. These chemical signatures are consistent with recent or immature, weakly developed soils, with a high stone or gravel content and little secondary clay mineral development. Cluster 1b1 soils occur along or immediately adjacent to recent floodplains or active stream channels of main stem and higher order stream and river systems across Southland (Figure 3-25).

At a pedogenic level, Cluster 1b1 soils are predominantly Recent > Brown > Pallic (Figure 3-22). Recent soils are predominantly Fluvial with minor Rocky and Sandy soils at the group level and Typic, Mottled, Mottled-Weathered and Weathered at the sub-group level. Brown soils are typically Pallic, Orthic Browns with minor Sandy Brown soils. Pallic soils are Pedal Immature, Mottled Laminar and

Brown Orthic Pallics. Typic Orthic and Typic Mafic Melanics make up the remainder of Cluster 1b1. Well- to moderately-well- drained soils predominate (84%) cluster 1b1. Imperfectly- (14%) and poorly- drained (2%) soils constitute the remaining soils which are mainly Mottled or Mottled-Weathered Fluvial Recent soils.

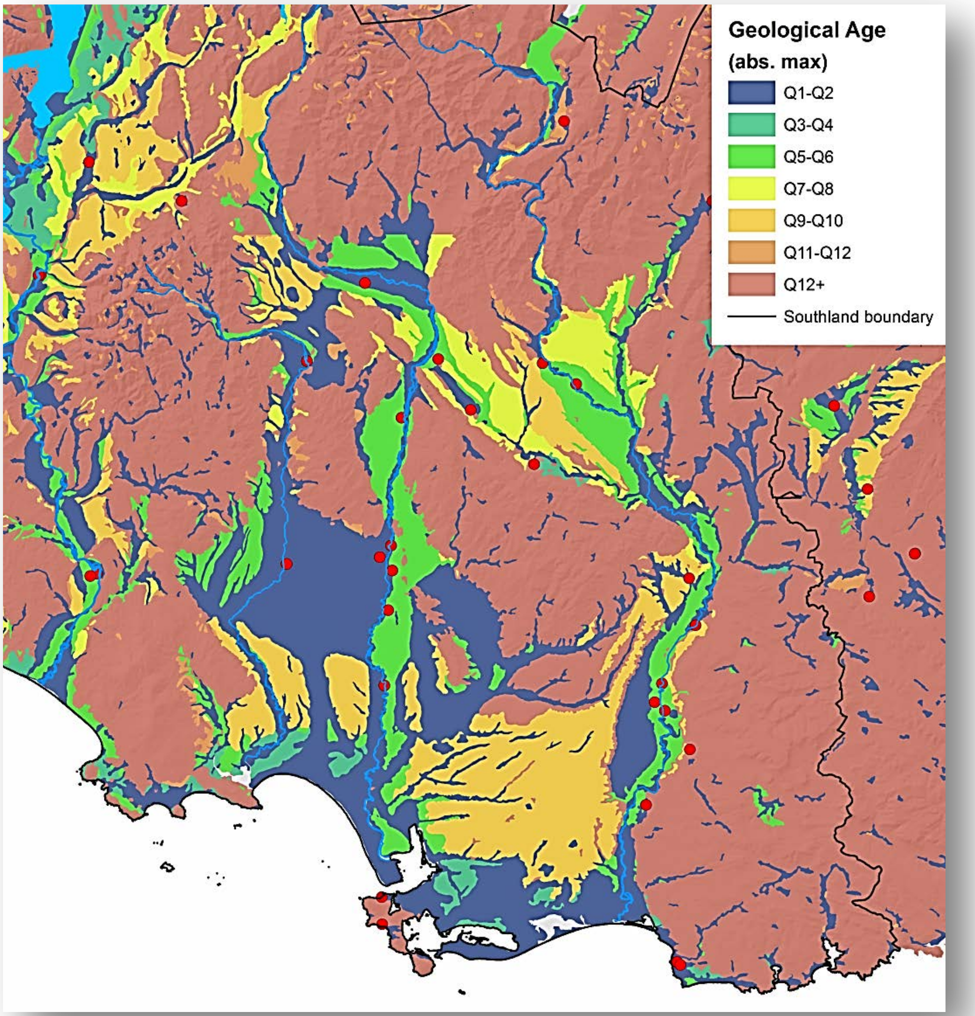

Figure 3-25: Cluster 1b1 distribution with geological age from Qmap (Heron, 2014).

Cluster 1b2

This is the largest of all the clusters with 149 individual profile points representing 43.5% of the dataset. Relative to the other clusters, 1b2 soils show characteristics that fall between Cluster 1a and Cluster 2 soils. BS% and pH is moderate (Figure 3-20), as is Ca, Mg and Na content compared to the other clusters, with values in Cluster 1a soils typically lower and Cluster 2 soils typically higher. K content is low, similar to that of group 1a1 (Figure 3-21). Spatially, Cluster 1b2 soils are associated with young (Q1al - Q2al) and intermediately aged (Q6 and up to Q8 – Q10) stable alluvial surfaces. These soils are overwhelmingly fine textured, silt, loam soils with low C% derived from loess and all have slow permeability (<4 mm/hr). With the exception of low latitude, gentle sloping hills of south eastern Catlins this Cluster is not associated with hill or high country bedrock (Figure 3-26).

At a pedogenic level, Cluster 1b2 soils are predominantly Brown > Pallic > Gley with minor Melanic, Allophanic and Ultic soils (Figure 3-22). Brown soils (n=82) are Firm, Orthic and Allophanic at the group level and predominantly Typic, Pallic, Mottled, Mafic, Acidic and Mottled-Pallic at the sub-group level. Pallic soils (n=48) are predominantly Fragic, Argillic-fragic, Typic and Argillic, Perch-gley Pallics with minor Mottled Fragic Pallic soils at the group and sub-group level. Gley soils (n=44) are Orthic and Recent at the group level and Typic, Acidic, Ironstone and Argillic at the sub-group level. These soils are typically poorly-drained (46%) with 23% imperfectly-drained and the remainder moderately-well- to well- drained.

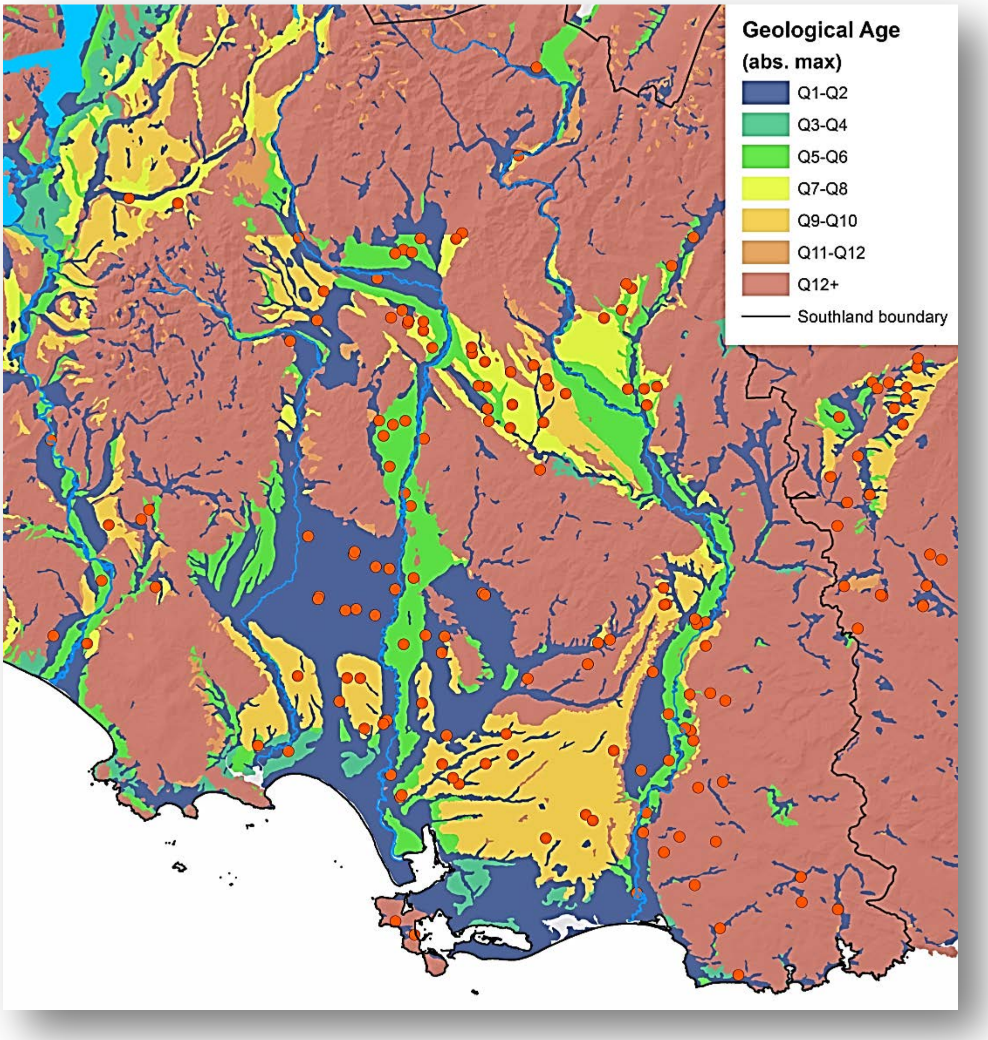

Figure 3-26: Cluster 2a1 distribution with geological age from Qmap (Heron, 2014).

Cluster 2a

Cluster 2a soils are distinguished from all other clusters by high BS%, exchangeable Ca, Mg and K (Figure 3-21). Percent clay is the highest of the clusters (although similar to 1a2 and 1b2) with medium C% and N% (Figure 3-20). Due to the generally high clay content and moderate C%, the CEC of Cluster 2a soils is the second highest of the six clusters. The C:N ratio is small, indicative of naturally fertile soils.

The soils of Cluster 2a appear to fringe mountainous or hilly outcrops of base rich parent materials including the Takitimu (Brook Street) and Matai (Dun Mountain) Groups as well as varied limestone and calcareous units that form some of the dominant landform features of Southland (Figure 3-27). These soils are also associated with sedimentary units that include tuff or shell beds across the Catlins. Cluster 2a soils are prominent across younger (<Q4) alluvial surfaces derived from

headwater catchments with prominent mafic assemblages or where calcareous rocks are present. Examples include: 1) the roughly triangular area between the Oreti and Makarewa Rivers where young (<Q4) alluvial surfaces and outcrops of the Forest Hill and Castle Downs Limestone appear to strongly influence soil BS%; and 2) the area between the Aparima and Oreti Rivers in association with younger (<Q4) alluvial surfaces derived from the mafic assemblages of the Takitimu Mountains. Cluster 2a soils are conspicuously absent across older, weathered surfaces formed in felsic parent materials (e.g. Kamahi and Waikiwi Terrace Formations).

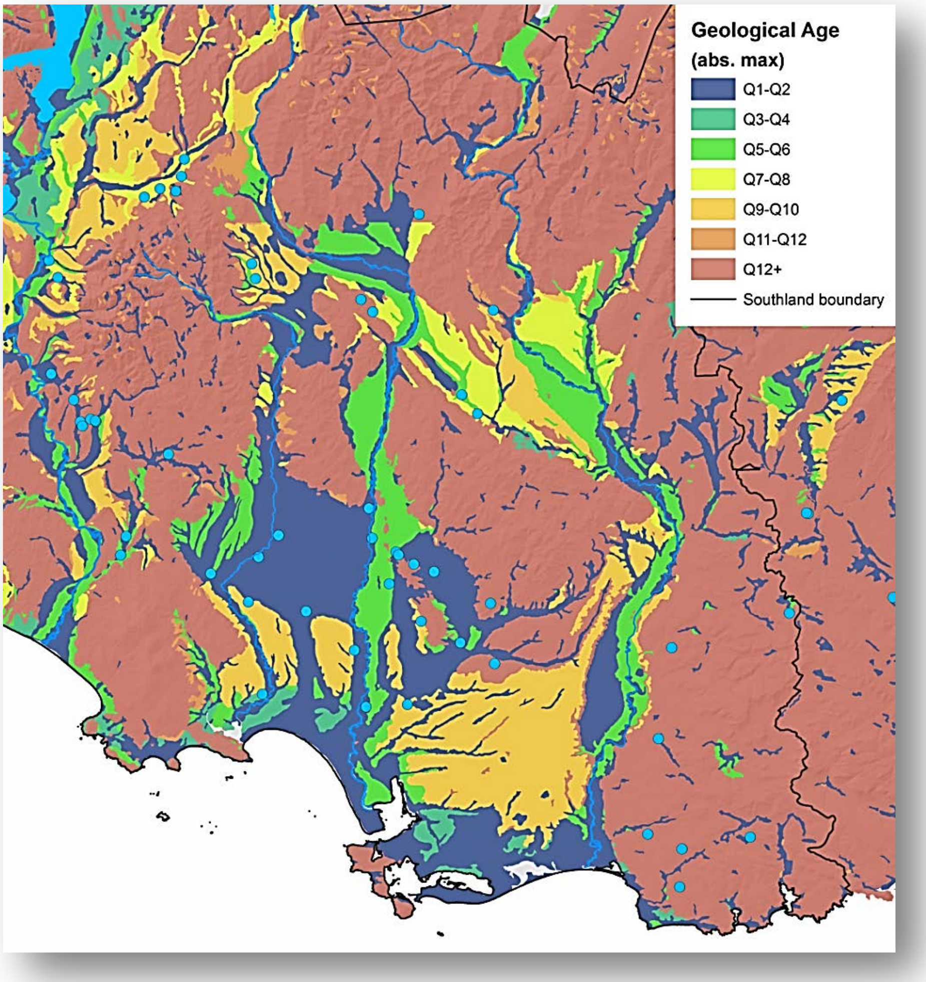

Figure 3-27: Cluster 2a distribution with geological age from Qmap (Heron, 2014).

At a pedogenic level, Cluster 2a soils are predominantly Brown and Gley soils with lesser Pallic, Melanic and minor Recent and Allophanic soils (Figure 3-22). Brown soils (n=19) are typically Orthic, Mafic, Firm and Allophanic. Typic > Acidic > Pallic are the main sub-groups. The Gley soils are mostly Orthic (n=16) with minor Recent (n=2) at the group level and Typic > Calcareous > Melanic = Argillic = Acidic at the sub-group level. This cluster has the largest number of Melanic soils as Typic Mafic and Argillic Orthic Melanics. The soil drainage classes within this cluster are split primarily between well-drained and minor moderately-well drained Brown and Melanic soils (52%) poorly-drained Gley soils and Perch-gley Pallics (37%) with minor imperfectly-drained Argillic and Immature Pallic soils (11%) soils.

Cluster 2b

Cluster 2b is the smallest cluster with 12 individual soil profiles. In Cluster 2b, C% is the highest (median 35.4%), C:N ratios have the largest range and pH (median 4.6) is the lowest of the six clusters. Exchangeable Na is elevated with the highest median of the six clusters. CEC is also the highest of all clusters (Figure 3-20 and Figure 3-21). These signatures suggest Cluster 2b soils are highly weathered soils with very-poor- to poor-drainage, high accumulations of organic carbon and in close proximity to the coast (Figure 3-28).

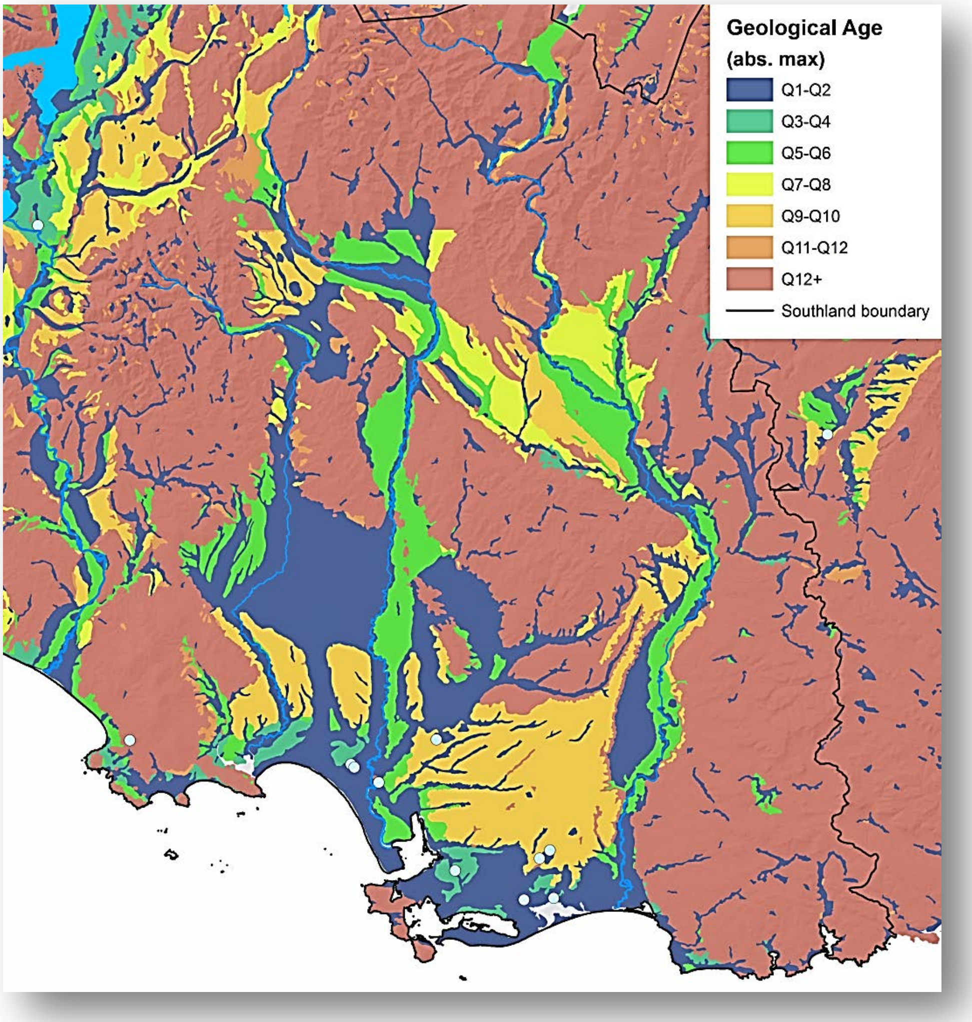

Figure 3-28: Cluster 2b distribution with geological age from Qmap (Heron, 2014).

Geomorphically, Cluster 2b soils show a strong association with low-lying, low order stream channels or old (Q8 and older) highly weathered landforms of coastal Southland. Cluster 2b soil locations include the lower half of the Waituna Catchment, low-lying, modern day floodplains of the Kamahi Formation and the most coastal occurrences of Southland hill country (e.g. areas of the Longwoods). Qmap provides a generic description of the setting for this soil cluster (Code: "Description") as "unconsolidated gravel; sand and peat in modern stream beds; flood plains with minor overbank swamps" for the large number of soil profile sites associated with low order stream channels (Q1 – Q2) dissecting old alluvial surfaces (>Q8) and "weathered sandy greywacke (quartz) gravel in high terraces, including dune sand" for old surfaces of Q8 – Q10 age (Heron, 2014).

At a pedogenic level, Cluster 2b soils consist of Organic (67%), Gley (25%) and minor Podzol soils (8%) (Figure 3-22). The Organic soils are mainly Acidic Humic (n=5) with individual profiles of Mellow Humic, Mellow Mesic and Buried-Podzol Litter Organic soils. The Gley soils are Peaty Orthic, Peaty Acidic, and Acidic Recent Gley soils. The Podzol soil represents one profile for a Humic Pan Podzol. The Organic and Gley soils are mostly very poorly- to poorly- drained (83%) with the Podzol soil imperfectly-drained and the Buried-Podzol Litter Organic soil well-drained. This profile is a variant of its series (Waihoaka) with the other soils in the series classified as well- to imperfectly- drained Humic Pan Podzols.

TC3.5 The relationship of HCA to PCA

HCA and PCA are both methods designed to elucidate the intrinsic controls inherent in a dataset without reference to prior categories or classification. Therefore, applied to the same dataset, a logical relationship between the results of each type of analysis might be expected and further explain the nature of the clusters and principal components identified in TC 3.3. The principal components are as follows: the age and degree of weathering of a soil which is positively correlated with land surface age (PC1); the parent material in which the soils form (provenance) (PC2); drainage class (PC3); clay formation (PC4) and an undetermined control over exchangeable bases. At a broad scale, the most influential principal components, PC1 and PC2, are aligned with the separation of three HCA clusters at the higher, 900 phenon level, and the less influential PC3 and PC4 associated with further subdivision into the six HCA clusters at the 500 phenon level.

TC3.5.1 PCA and HCA at the 900 phenon line

As described in TC 3.3.1, PC1 is associated with soil weathering, with the most weathered soils showing the most positive ratings. At the 900 phenon level of HCA it is seen that soils in clusters 1a and 1b show mostly negative values for PC1 while soils in Cluster 2 are mostly positive (Figure 3-29). Cluster 2 is therefore identified as containing the most weathered soils; as will be seen at the 500 phenon level however, this encompasses two quite different aspects of weathering.

Clay is a key indicator of soil weathering, which is most often and mostly, in the case of Southland soils, formed by pedogenic processes within soil rather than being contained in the raw deposit of a parent material. This is because it forms from the weathering products of primary minerals. Cluster 2 includes the most clay-rich soils of the dataset, though this is best appreciated by examining the sub-clusters 2a and 2b, with the clay-rich soils residing in 2a.

Organic matter is also associated with weathering, taking time to accumulate in soil from the breakdown of litter, and thereafter contributing acids required for weathering of soil mineral material. For this reason the Organic soils (i.e. Cluster 2b) score highly for PC1, though whether this relates to the weathering of the small components of mineral material in these soils, or simply to the low pH and high C% otherwise associated with weathering, is unclear.

Clusters 1a and 1b, while containing some weathered soils, do not clearly exhibit the combination of properties characterising Cluster 2, including low pH relative to clay content. PC1, the principal component of highest influence, is therefore diagnostic of the separation of clusters at the highest level of HCA.

PC2 is associated with soil parent materials, with base-rich materials at one end and felsic materials at the other (negative) end of a continuum (see TC 3.3.2). As with a number of other properties, the sub-clusters 2a and 2b show very different characteristics with regard to BS%, exhibiting the highest and lowest median BS% respectively. Despite this, the concentrations of base cations in Cluster 2 soils are consistently high (being offset by very high levels of acidic cations in 2b), resulting in mostly positive weightings for Cluster 2 soils. But it is in the separation of clusters 1a and 1b that PC2 contributes most to understanding of the HCA clusters.

Among the three clusters at 900 phenon level, only 1a shows largely negative weightings for PC2. This reflects low concentrations of Ca and Mg, the most abundant basic cations in most soils. Cluster 1a also has lower median pH and base saturation than clusters 1b and 2. Therefore, while the primary separation of clusters 1a,1b and 2 relates to the degree of weathering. The separation of 1a and 1b relates more to parent materials. These separations are not primarily related to soil orders, which are well spread across the three high level clusters (see Figure 3-14).

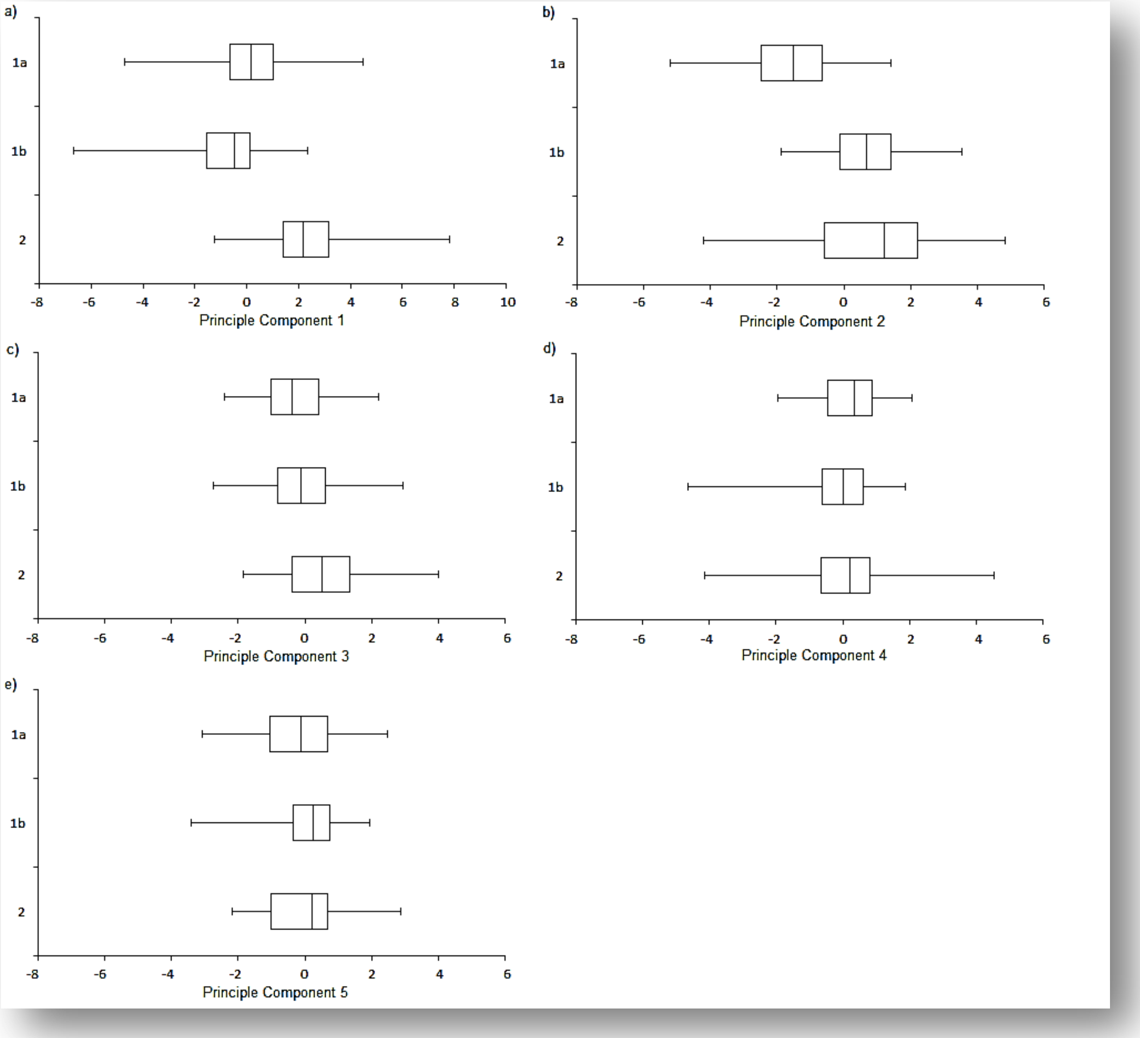

Figure 3-29: Hierarchal clusters (900 Phenon line) by principal components a) PC1 weathering, b) PC2 parent material, c) PC3 drainage, d) PC4 P-retention, and e) PC5 undetermined.

TC3.5.2 PCA and HCA at the 500 phenon line

As described in TC 3.4.2, each of the clusters, 1a, 1b and 2, is further separated into two sub-clusters at the 500 phenon level by HCA analysis. Following its association with the primary separation of clusters 1a, 1b and 2, PC1 representing soil weathering, is further associated with the subdivision of each of these into its two sub-clusters. Of these sub-clusters, 1a2, 1b2 and 2b are weighted more highly for PC1 than the corresponding 1a1, 1b1 and 2a, the latter representing less weathered soils. Clusters 2a and 2b are however, both more highly weighted for PC1 than any other clusters at the 500 phenon level, indicative of the separation of cluster 2 at the higher level (Figure 3-30).

Sub-clusters 1a2, 1b2 and 2b are further separated from the corresponding 1a1, 1b1 and 2a by PC3, associated with soil drainage and leaching. In 1a1 and 1a2, poor drainage in the latter is associated with higher Ca and Mg. In 1b1 and 1b2, poor drainage in the latter is associated with higher clay content. Clusters 2a and 2b are further differentiated by PC4, strongly linked to P-retention, which is high in the clay-rich soils of 2a but low in the Organic soils of 2b (see TCs 3.3.3 and 3.3.4 and Figure 3-30).

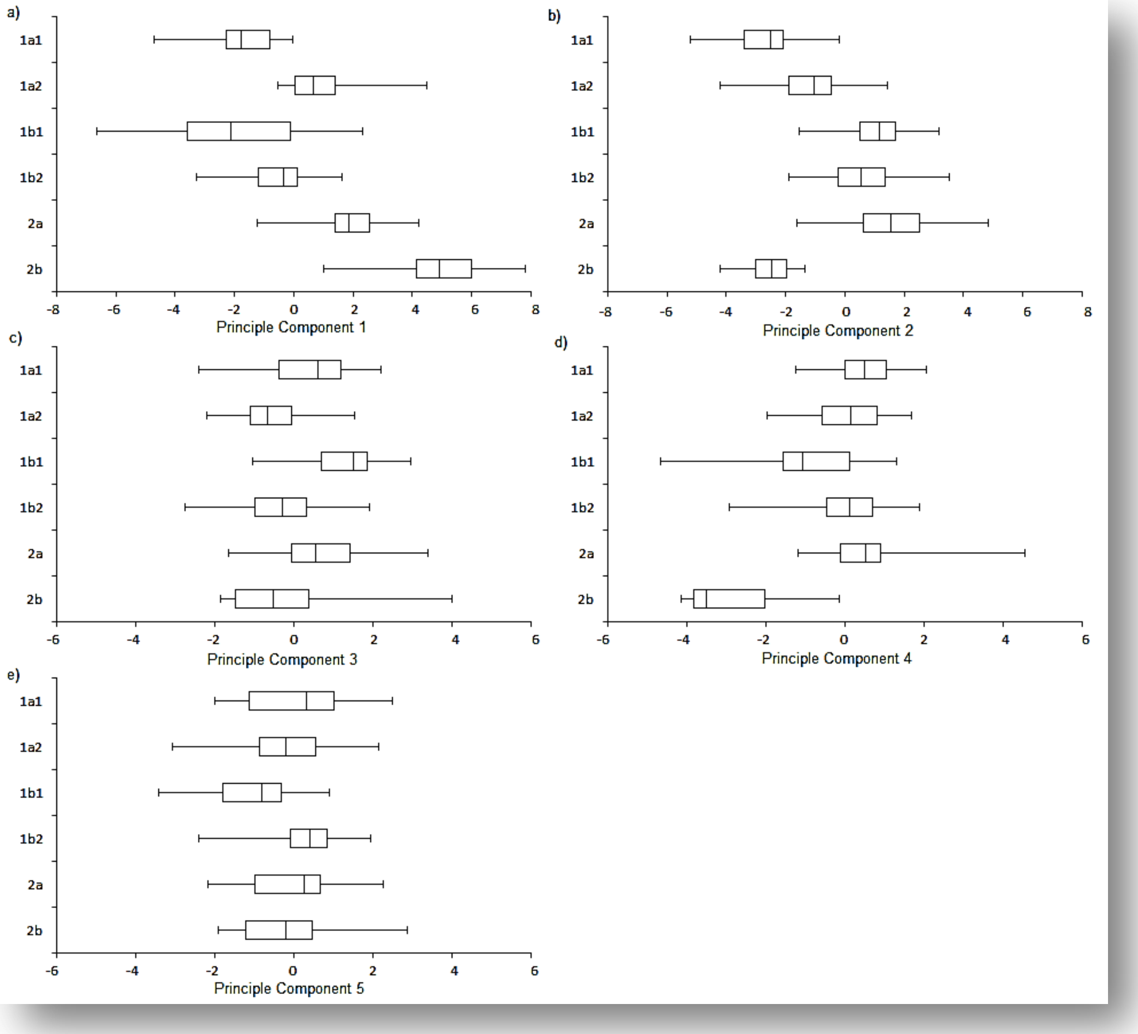

Figure 3-30: Hierarchal clusters (500 Phenon line) by principal components a) PC1 weathering, b) PC2 parent material, c) PC3 drainage, d) PC4 P-retention, and e) PC5 undetermined.

TC3.6 Soil Denitrification Potential

One way in which soils influence the chemistry of groundwater recharge waters is by attenuating nitrate via denitrification. For denitrification to occur in soil, four requirements must be met: nitrate availability, oxygen-depleted conditions, electron donor availability (i.e. organic matter) and the presence of denitrifying microbes. In agricultural landscapes, oxygen-depletion and electron donor availability are most often the critical requirements.

Direct and quantitative investigations of soil denitrification potential are lacking at the regional scale. Killick et al. (2015) assigned soil denitrification potential (SDNP) rankings to soils of the agricultural lands of Southland described in the Topoclimate South soil survey (Figure 3-31). The rankings, which are qualitative only, were based on organic matter content, indicators of oxygen depletion found in soil profile descriptions and supplementary data from the Topoclimate survey.

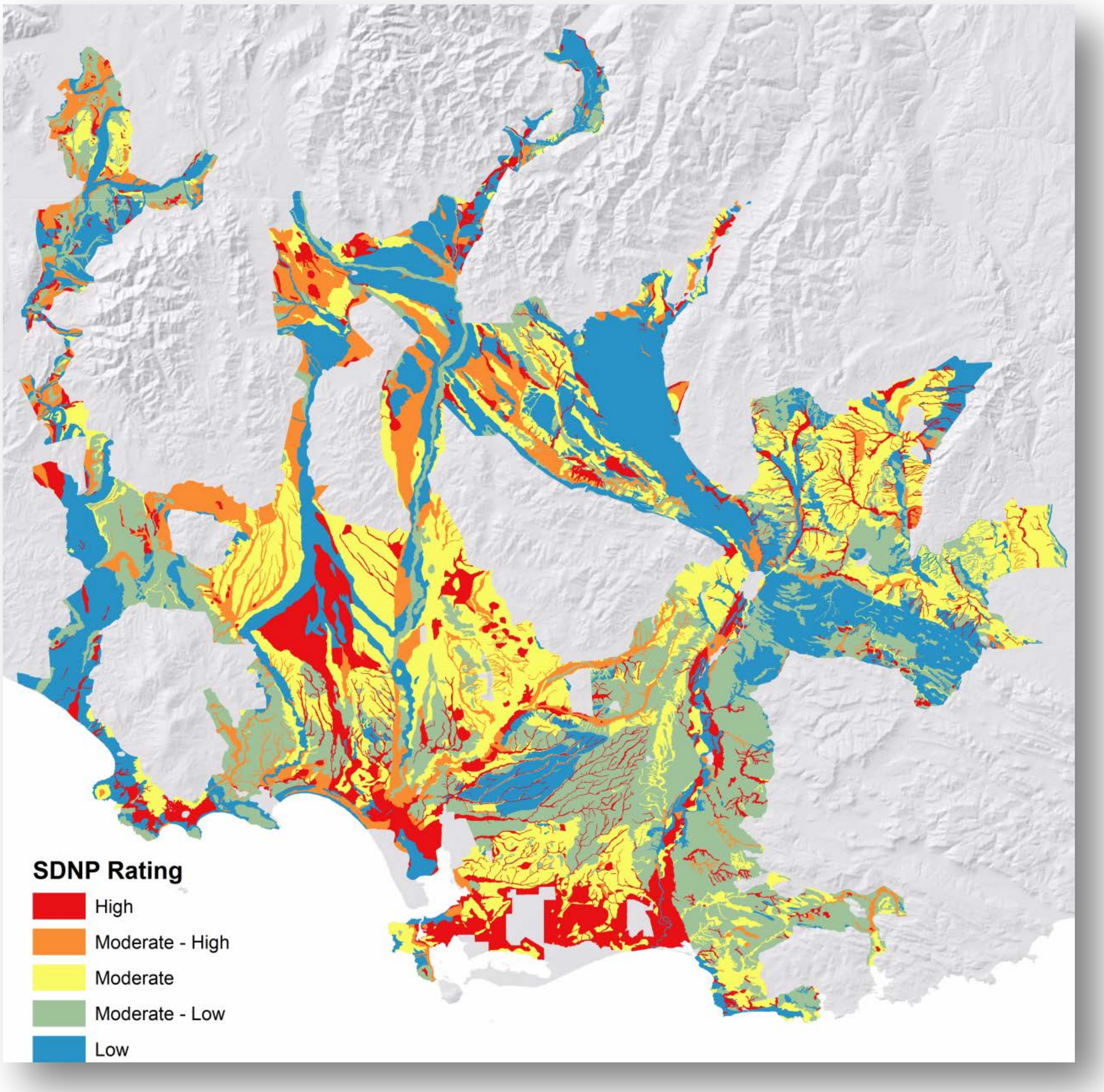

Figure 3-31: Soil denitrification potential in Southland (Killick et al., 2015).

Of the five principal components described above, all but PC2 are correlated to SNDP. PC1 is associated with soil evolution and weathering and is positively correlated to SNDP. Organic matter, one of the key factors in the SNDP ranking, accumulates over time as soil matures, and is also positively correlated with PC1. Organic, Gley and Podzol soils are ranked most highly on average for SNDP (Pallic soils are also ranked relatively highly on the strength of the Perch-gley Pallic soils, which are prominent in Southland). Organic and Podzol soils are also the most highly ranked for PC1.

Allophanic soils, uncommon in Southland, were rated highly for PC1 but moderately low for SNDP. These soils are considerably weathered but have only moderate accumulation of organic matter. Their tendency to waterlogging is also minimal, hence oxygen depletion is rare. These factors combined to produce the moderately low SNDP rankings of Allophanic soils. Furthermore, the Topoclimate examples of these soils were of shallow depth over rock; this further contributed to their low SNDP scores, as the rating system gave higher SNDP ratings to deeper soils.

PC3 and PC4 are positively correlated with drainage class and negatively correlated with SNDP. This is expected because soil denitrification is favoured by poor drainage, which causes oxygen depletion. PC4 is also negatively correlated with C%, supporting its negative correlation with SNDP, as carbon in soil is an electron donor for denitrification. PC5 is negatively correlated with drainage class and positively correlated with C%, it therefore shows a positive correlation with SNDP.

As with PCA analysis, SNDP rankings were not included in the HCA analysis considered here however, the characteristics of the soil HCA clusters are as expected with regard to SNDP (Figure 3-32). Cluster 2 high in organic matter, shows the highest average SNDP. This cluster also includes many poorly-drained soils which are subject to oxygen depletion as described below.

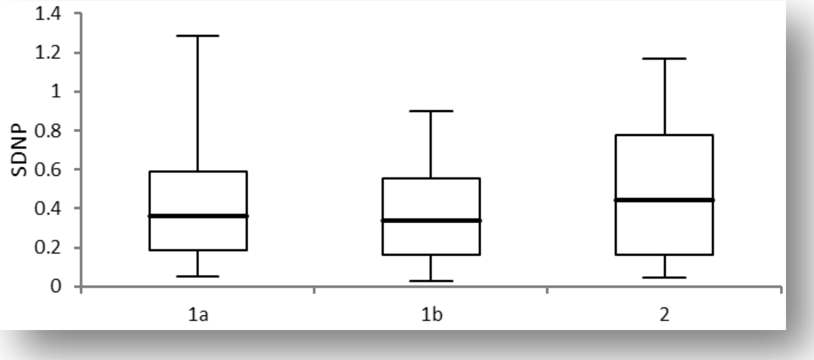

Figure 3-32: HCA (at 900 phenon line) showing average SDNP ranking of soils in each cluster.

Of note at the 500 phenon line is Cluster 2b, dominated by soils with high organic matter such as Podzols and Organic soils, giving the highest average SNDP (Figure 3-33). Clay content and drainage class are instrumental in sub-dividing clusters 1a and 1b, with the more clayey, poorly-drained 1a2 and 1b2 showing the higher SNDP.

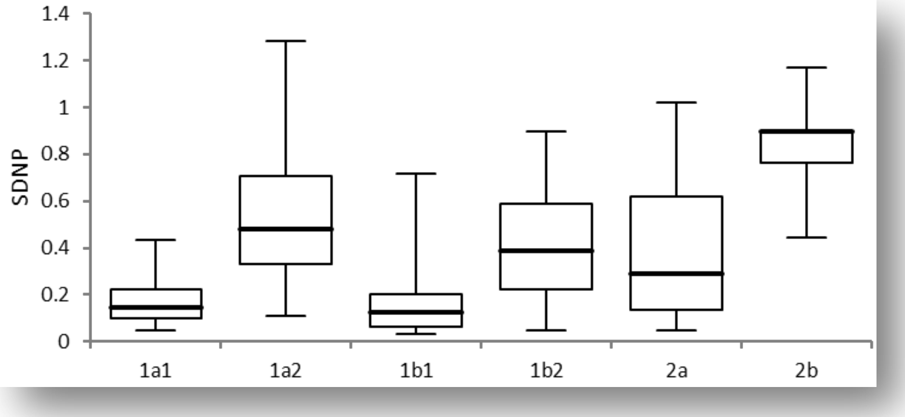

Figure 3-33: HCA (at 500 phenon line) showing average SDNP ranking of soils in each cluster.

TC3.7 Summary

In summary, both PCA and HCA in conjunction with geomorphic and geological age indicate that soil weathering (landform age), parent materials, drainage class, clay retention of P and an undetermined control over exchangeable bases are the main factors governing soil chemical variation across Southland. The spatial variation in chemistry of Southland soils is therefore determined primarily by:

(i) the age and degree of weathering of a soil, which is positively correlated with geomorphic land surface age;

(ii) the parent material (PM) the soils form in (provenance);

(iii) low-lying areas with a high water table versus elevated areas with a low water table,

(iv) clay formation and;

(v) exchangeable bases.

Specifically, at a high level HCA identified three main groups of soils with distinctly different soil chemical characteristics before further resolution into six key soil chemical clusters. Importantly, soils that have similar chemical characteristics all showing considerable range in terms of pedogenic order, group and sub-group. Although greater chemical uniformity is apparent at the subgroup level, traditional pedogenic characterisation appears too coarse to identify soils of similar chemical characteristics (see also Daughney et al., 2015). This suggests that soil chemical characteristics are likely more important controls on water quality than soil order and soil series. Although soil drainage class is variable and the resolution of drainage class is poor relative to the site of soil chemical sampling, some broad general relationships are observed (Table 3-9; see also Daughney et al., 2015).

The value of this approach is that through application of PCA to the soil chemical data, the controls over the variability of soil chemistry can be resolved. Specifically, the relative significance of key soil forming factors over soil chemical variability can be quantified and ranked in order of importance. The first principal component captures the maximum variation in the data set, whereas the second principal component has the next most variation and so on.

HCA is a data driven approach for which no prior assumptions are made as to the grouping of data; it is an agglomerative method for finding clusters of observations within a data set where soil chemical properties for each soil profile point are defined by a set of numeric variables; each object is positioned in a multi-dimensional space proportional to the number of variables used to define the object. HCA therefore provides an objective, data-driven approach to the grouping of soil with similar chemical characteristics. We note the limitations of this approach are a factor of the data inputs. For example, there is limited information on extractable Fe which may have provided important insight over soil drainage and redox conditions[4]. As with any method, unless data pertaining to certain key processes are included the output will tell you nothing about a given process. However, we feel the variables included within both the PCA and HCA run are as extensive as possible given the nature of the data set.

Combining both HCA and PCA with a knowledge of soil chemistry and geological/geomorphological relationships we are able to deduce both the relative importance of factors controlling the variability in soil chemistry as well as their spatial distribution. Such knowledge is essential for understanding

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[4] Although in this instance we may be able to overcome this limitation by inferring Fe data through the use of pedotransfer function created on the basis of extractable Fe data (& Al & Si) using Tamms, and citrate-dithionate extractions.

the role soils play in the hydrochemical evolution of regional ground- and surface- waters and therefore water quality outcomes. Specifically, in TC 4 and TC 5 we will demonstrate that soil chemical characteristics (especially pH, BS% and C%), not soil order, are the most critical factors over the chemical evolution of infiltrating precipitation.

Table 3-9: Summary of soil types and characteristics in clusters defined by HCA of soil profile analyses.

	Cluster characteristics		Sub-cluster characteristics
1a	**Soils with medium CEC, low BS%, high P-retention.** Negative for PC1 and PC2.	**1a1**	**Lower BS%, Ca and Mg than 1T2. Well-drained.** A tendency to higher pH than 1T2. Mostly Brown soils. Positive for PC3.
		1a2	**Higher BS%, Ca and Mg than 1a1. Imperfectly- to poorly- drained.** A tendency to lower pH than 1a1. Mostly Brown and Gley soils. Negative for PC3.
1b	**Soils with medium CEC, low C%, low P-retention.** Negative for PC1, positive for PC2.	**1b1**	**Lower clay% than 1b2. Well-drained.** A tendency to higher BS% and pH than 1b2. Mostly Recent, Brown and Pallic (not Perch-gley) soils. Positive for PC3, negative for PC5.
		1b2	**Higher clay% than 1b1. Imperfectly- to poorly-drained.** A tendency to lower BS% and pH than 1b1. Mostly Brown, Gley and Perch-gley Pallic soils. Negative for PC3, positive for PC5.
2	**Soils with high CEC.** Positive for PC1 and PC2.	**2a**	**Soils with high CEC from clay, medium C%. Well- to poorly-drained.** Mostly Brown, Gley and Perch-gley Pallic soils. Positive for PC3 and PC4.
		2b	**Soils with high CEC from organic matter, very high C%, very low pH. Poorly- to very poorly- drained.** Organic, Gley and Podzol soils. Negative for PC3 and PC4.