Objective:

The purpose of this investigation has been to consider compositions of water quality data from two mine tailing treatment experiments. These data were assessed for evidence of statistically significant differences as a function of treatment condition, depth and time. The experimental data were obtained as part of studies conducted by Boojum Research Limited that were designed to test the influence of phosphate rock applications with or without amendments of horse manure in controlling acid mine drainage.

Background (From Boojum Research Limited):

On both Stanrock (uranium tailings after sulphric acid leach) and on the Inco (fresh Cu and Ni tailings with pyhrrotite) plots were set up, with parallel treatments. The treatments were applied to determine if the PHITO concept , heterotrophs consuming oxygen and phosphate to react in the vadose zone with oxidized iron, would form a layer which would not allow further infiltration, or would reduce infiltration of atmospheric precipitation.

Methods:

Data of hydrogen ion concentration (pH), total dissolved solids (TDS) or conductivity (μS/cm), acidity, oxidation-reduction potential (ORP or Eh in mv), and phosphorous concentration (mg-P/L) were provided as a function of time (months), depth (cm) and treatment condition. The analytical approach that was used considered the collection of aggregate water quality parameters obtained during the monitoring period as a fingerprint for discriminating differences in water quality. The statistical question being asked of the data was whether or not there were well defined differences in water quality between and within treatment plots as distinguished in time, depth and/or treatment condition. Water quality compositions were analysed by Logcontrast canonical component analysis.

Results and Discussion:

In total there were six experimental conditions that will be referred to as conditions A to F corresponding to the treatments listed in Table 1. The data from the experiments on the Stanrock and Inco tailings will be referred to simply as Stanrock (Table 2) and Inco (Table 3) data.

In order to consider the sets of water quality data as observations in composition, it was necessary to reduce the tables of data into a non-dimensional form with each water quality parameter scaled to nondimensional ranges of similar magnitude. The readings of pH, ORP, TDS, acidity and phosphorous were therefore normalized by their respective arithmetic means that are also reported in Table 2 and 3, respectively.

The next objective was to define the respective compositions as the relative proportion of a set of normalized water quality parameters. Of the parameters measured, pH, ORP, TDS and acidity could be considered as independent aggregate measures of the water sample quality. Total phosphorous (TP) is a specific water quality metric and was also directly related to one of the treatments being applied (phosphate rock). Therefore, TP was not considered to be

Table 1. Table of Treatment Conditions

Label	Treatment Condition (amendment)
A	Control (no amendments)
B	High Horse manure (HM)
C	Low phosphate rock (PR)
D	High HM and Low PR
E	High PR
F	High HM and High PR

wholly applicable nor absolutely independent and so was not included for the compositional analysis. The water quality was considered to be defined by the set of aggregate measurements as follows:

$$w_i = \left\{ \frac{pH_i}{\overline{\overline{pH}}}, \quad \frac{Eh_i}{\overline{\overline{Eh}}}, \quad \frac{TDS_i}{\overline{\overline{TDS}}}, \quad \frac{Acidity_i}{\overline{\overline{Acidity}}} \right\}$$

where w_i would be the i^{th} row or one record from the data presented in Table 2 and 3. It was observed that for the Stanrock data TDS and acidity were correlated to one and other (Figure 1). The range of TDS and acidity observed for the Stanrock and Inco data also suggested that there were essential differences between the parallel experiments conducted at the two separate sites (Figure 1). Some degree of positive correlation could similarly be observed between pH and TDS or TDS and acidity (Figure 2). It was logical to observe that low pH values were typically found under conditions of high acidity (total dissolved solids) and that more metals were dissolved under lower pH conditions. Of all the aggregate water quality parameters measured, the electrochemical potential appeared to exhibit minimal, if any, correlation to any other component (Figure 3).

Therefore, not all the compositional elements were absolutely independent of one and other. The benefit of canonical component analyses is that the multidimensional water quality data would become transformed into a coordinate system of mutually orthogonal elements that could be directly compared.

In compositional analysis, it is the relative proportions of the elements that are compared. The basis (b) for each observation is defined by the sum of the four non-dimensional elements:

$$b_i = \frac{pH_i}{\overline{\overline{pH}}} + \frac{Eh_i}{\overline{\overline{Eh}}} + \frac{TDS_i}{\overline{\overline{TDS}}} + \frac{Acidity_i}{\overline{\overline{Acidity}}}$$

Thus, the compositions being considered by Logcontrast canonical component analysis in this report are the compositional vectors (w_i) normalized by their corresponding basis:

$$\omega_i = \frac{1}{b_i} \left\{ \frac{pH_i}{\overline{\overline{pH}}}, \quad \frac{Eh_i}{\overline{\overline{Eh}}}, \quad \frac{TDS_i}{\overline{\overline{TDS}}}, \quad \frac{Acidity_i}{\overline{\overline{Acidity}}} \right\}$$

Table 2. Stanrock data as received for statistical analysis with TDS in µS/cm, Acidity in mg-$CaCO_3$/L and TP in mg-P/L.

			pH	Eh	TDS	Acidity	TP
		Average	3.51	727	3261	1392	3.80
		σ	1.66	86	2154	2018	6.39
		C_v	47%	12%	66%	145%	168%
Condition	**depth (cm)**	**time (mo)**	**pH**	**Eh**	**TDS**	**Acidity**	**TP**
A	7.5	0.001	2.92	804	2470	378	0.25
A	7.5	0.236	2.62	749	3090	606	0.26
A	7.5	6	2.42	768	3024	597	0.23
A	7.5	18	2.70	763	2920	570	0.74
A	7.5	21	2.67	735	2302	443	
A	22.5	0.001	2.50	714	3690	2070	1.31
A	22.5	0.236	2.46	687	4110	2238	1.26
A	22.5	6	1.94	796	5715	4013	1.33
A	22.5	18	2.04	818	7840	5503	2.21
A	22.5	21	1.86	844	5440	4302	
B	7.5	0.001	2.84	827	2520	298	0.20
B	7.5	0.236	2.57	755	3230	533	0.14
B	7.5	6	2.17	804	4224	1042	0.28
B	7.5	18	2.80	763	3384	518	6.89
B	7.5	21	2.68	762	2534	391	
B	22.5	0.001	3.00	861	2390	415	0.30
B	22.5	0.236	2.69	747	2840	417	0.17
B	22.5	6	2.43	755	3048	457	0.29
B	22.5	18	3.39	665	2404	114	0.72
B	22.5	21	3.37	702	1507	70	
C	7.5	0.001	2.94	764	2480	418	1.20
C	7.5	0.236	2.78	717	2720	507	1.33
C	7.5	6	2.41	791	2667	787	2.61
C	7.5	18	2.86	785	1650	261	1.15
C	7.5	21	2.77	795	1326	209	
C	22.5	0.001	2.41	702	4460	2788	8.75
C	22.5	0.236	2.35	684	4940	2952	11.10
C	22.5	18	2.05	721	11760	8023	19.77
C	22.5	21	1.82	870	9350	7200	
D	7.5	0.001	4.28	824	1980	35	0.13
D	7.5	0.236	4.12	659	2010	40	0.68
D	7.5	18	4.50	589	2230	121	3.65
D	7.5	21	4.52	676	1550	35	
D	22.5	0.001	4.84	767	1950	25	0.33
D	22.5	0.236	4.56	658	1970	15	0.76
D	22.5	6	4.34	704	1600	23	1.37
D	22.5	18	4.47	581	936	22	0.35
D	22.5	21	4.45	613	434	11	
E	7.5	0.001	6.06	749	1950	12	0.13
E	7.5	0.236	6.11	567	2000	24	0.36
E	7.5	6	7.13	685	1760	9	0.41
E	7.5	18	7.17	578	1346	9	0.51
E	7.5	21	6.75	585	631	15	
E	22.5	0.001	2.73	682	2940	733	3.21
E	22.5	0.236	2.66	702	3130	838	2.19
E	22.5	6	2.11	700	4514	2018	19.30
E	22.5	18	2.24	819	6502	4219	22.92
E	22.5	21	1.99	839	5846	4095	
F	7.5	0.001	5.86	762	1960	16	0.18
F	7.5	0.236	6.14	565	2000	24	0.26
F	7.5	6	7.18	678	1881	13	0.64
F	7.5	18	6.79	570	1666	28	0.67
F	7.5	21	7.37	509	885	5	
F	22.5	0.001	2.57	732	3470	2167	9.35
F	22.5	0.236	2.48	722	3880	2586	9.70
F	22.5	6	1.88	784	6532	5608	24.91
F	22.5	18	2.20	837	7009	5699	10.26
F	22.5	21	1.83	856	4565	4157	

Table 3. Inco data as received for statistical analysis with TDS in µS/cm, Acidity in mg-$CaCO_3$/L and TP in mg-P/L.

			pH	Eh	TDS	Acidity	TP
		Average	3.49	652.26	2200.47	652.05	0.31
		σ	0.40	66.91	958.27	609.96	0.56
		C_v	12%	10%	44%	94%	181%
Condition	**depth (cm)**	**time (mo)**	**pH**	**Eh**	**TDS**	**Acidity**	**TP**
A	7.5	0.001	3.50	577	1280	298	0.10
A	7.5	0.236	3.05	688	1860	456	0.09
A	7.5	6	2.98	655	2932	1538	0.36
A	7.5	18	3.21	670	2862	1677	0.10
A	22.5	0.001	3.82	613	788	66	0.04
A	22.5	0.236	3.62	576	1380	197	0.19
A	22.5	6	3.08	673	2367	652	0.33
A	22.5	18	3.19	682	3528	1446	0.22
B	7.5	0.001	3.32	684	1910	516	0.22
B	7.5	0.236	3.14	731	2670	901	0.11
B	7.5	6	2.86	634	4524	1963	0.26
B	7.5	18	3.23	686	4014	2128	0.19
B	22.5	0.001	3.57	728	1110	168	0.02
B	22.5	0.236	3.36	647	1820	402	0.13
B	22.5	6	2.98	629	2903	940	0.61
B	22.5	18	3.22	675	3234	1420	0.16
B	38.0	0.001	4.14	573	770	30	0.03
B	38.0	0.236	3.95	540	1260	117	0.07
B	38.0	6	3.23	662	3210	600	0.43
B	38.0	18	3.51	539	2450	490	0.17
B	61.0	0.001	4.24	625	670	19	0.12
B	61.0	0.236	4.42	609	1140	145	0.03
B	61.0	6	3.43	668	2008	235	0.23
B	61.0	18	3.40	699	2595	907	0.15
C	7.5	0.001	3.87	633	770	64	0.02
C	7.5	0.236	3.53	592	1420	222	0.04
C	7.5	6	3.05	683	3018	844	0.31
C	7.5	18	3.20	728	3328	1593	0.17
C	22.5	0.001	3.91	631	760	59	0.03
C	22.5	0.236	3.62	580	1360	186	0.06
C	22.5	6	3.00	663	2579	791	0.42
C	22.5	18	3.09	686	3653	1617	0.31
C	75.0	0.001	4.33	597	667	25	0.08
C	75.0	0.236	4.51	448	1150	129	0.05
C	75.0	6	3.47	654	1944	191	0.27
C	75.0	18	3.41	693	2940	916	0.29
D	7.5	0.001	3.42	708	1470	279	0.07
D	7.5	0.236	3.24	682	2290	573	0.14
D	7.5	6	3.02	551	3255	1303	0.45
D	7.5	18	3.27	680	2275	1126	0.23
D	22.5	0.001	3.74	610	740	84	0.04
D	22.5	0.236	3.53	621	1430	211	0.05
D	22.5	6	3.00	698	2754	914	0.52
D	22.5	18	3.20	709	3822	1629	0.29
D	70.0	0.001	3.86	640	1149	46	0.05
D	70.0	0.236	4.32	546	1790	168	0.02
D	70.0	6	3.30	585	2898	489	0.33
D	70.0	18	3.33	679	3886	1449	0.24
E	7.5	0.001	3.39	772	1630	431	0.06
E	7.5	0.236	3.45	698	2330	589	0.43
E	7.5	6	3.53	635	2738	518	1.63
E	7.5	18	3.79	644	2415	477	4.13
E	22.5	0.001	3.80	779	1090	118	0.05
E	22.5	0.236	3.60	619	1590	284	0.11
E	22.5	6	2.95	608	3042	978	0.58
E	22.5	18	3.10	718	3582	2170	0.29
E	65.0	0.001	3.75	793	1114	83	0.06
E	65.0	0.236	3.60	593	1650	235	0.07
E	65.0	6	3.45	651	2567	292	0.33
E	65.0	18	3.49	690	3150	932	0.40
F	7.5	0.001	3.44	790	1660	147	0.04
F	7.5	0.236	3.65	670	2270	260	0.18
F	7.5	6	4.10	616	2357	159	1.11
F	7.5	18	4.59	530	2010	64	1.87
F	22.5	0.001	3.64	818	1150	176	0.09
F	22.5	0.236	3.56	650	1650	294	0.18
F	22.5	6	2.99	590	2756	908	0.41
F	22.5	18	3.17	708	3204	1417	0.25
F	65.0	0.001	3.67	733	1370	214	0.20
F	65.0	0.236	3.64	651	1910	408	0.12
F	65.0	6	2.93	588	3217	1197	0.58
F	65.0	18	3.17	661	3349	2379	0.11

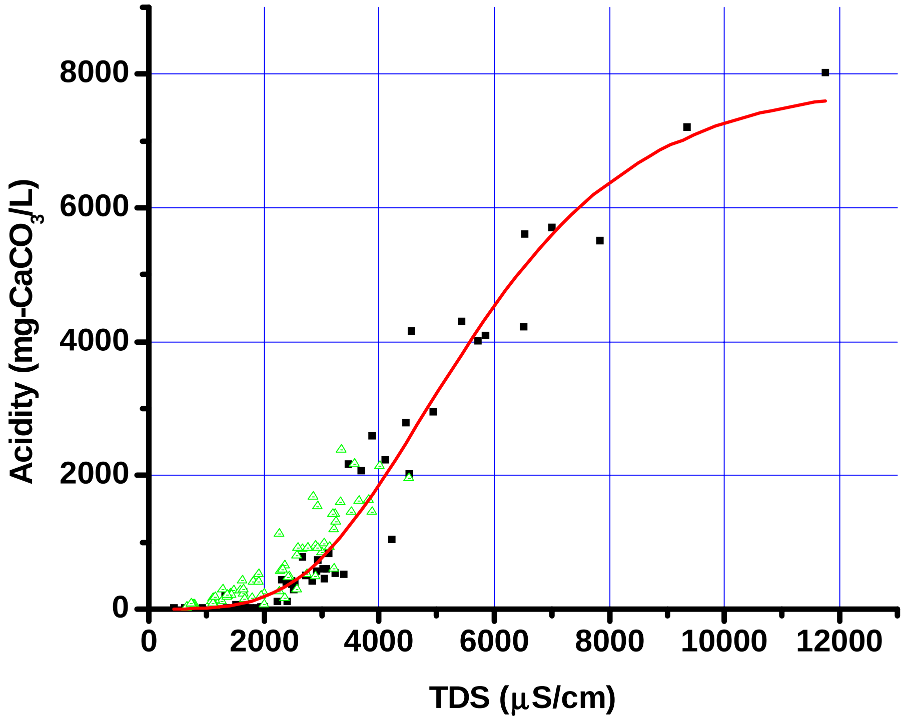

Figure 1. Correlation between TDS and Acidity for the Stanrock (■) and Inco (Δ) data.

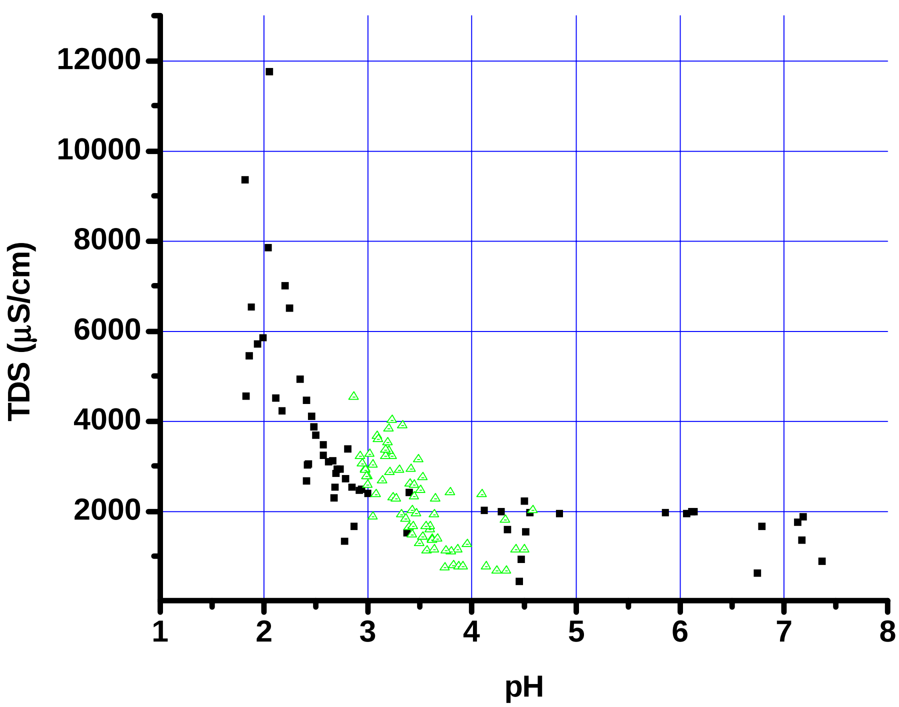

Figure 2. Correlation between pH and TDS for the Stanrock (■) and Inco (Δ) data. TDS tends to decrease as pH values increase above 3.

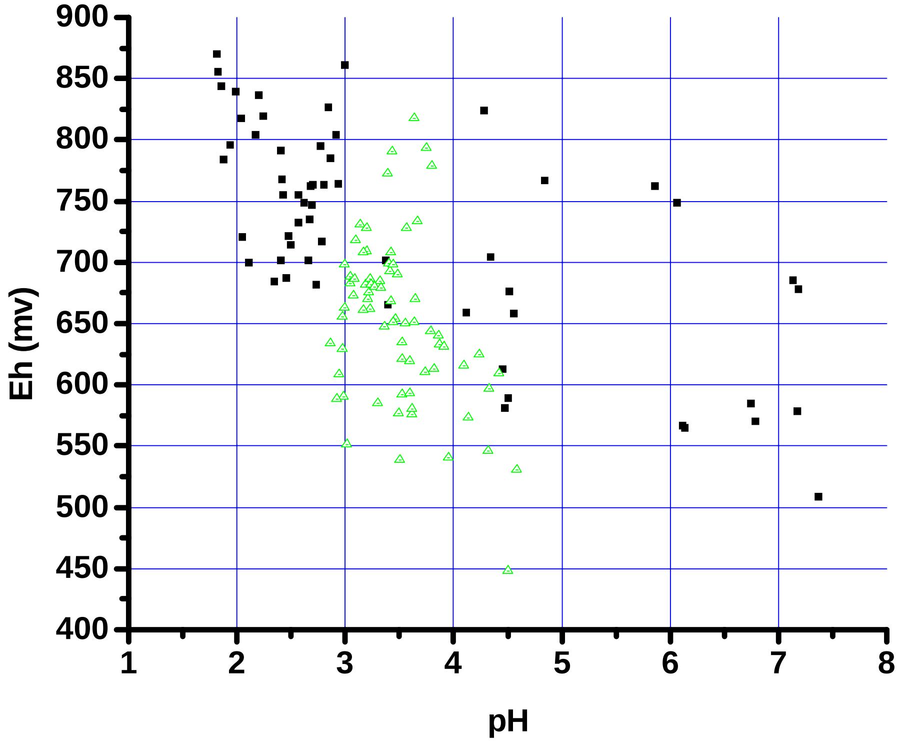

Figure 3. Scatter graph of pH versus Eh for the Stanrock (■) and Inco (Δ) data.

If the water quality were to be quite dynamic over time, one would expect to observe changes in both the ω-vector and its associated basis (b).

Logcontrast canonical and principal component analyses were applied to the data of water quality compositional vectors in order to address the following questions:

1. *Did the treatment conditions A to F generate distinct or similar water quality with respect to one and other within the Stanrock and Inco experiments?*
2. *Did the water quality exhibit a depth dependence?*
3. *Was the water quality relatively stable in time?*

The first analysis examined the water quality compositional data for evidence of differences between treatment conditions at the mean sampling depths of 7.5 and 22.5 centimetres. Logcontrast canonical component analysis was performed to contrast the within treatment variability in time versus the between treatment water quality compositional variability. In all cases the first canonical component expressed virtually all the between treatment variance. Therefore the data has been presented as a *scaled* discriminant score (Figures 4, 5, 6 and 7).

The effect of scaling is to align all the results from the compositional analysis performed on the different sets of the data obtained from Tables 2 and 3 into a uniform scale for purposes of direct comparison. For example, note that the exhibited level of between treatment discrimination for the Stanrock data (Figures 6 and 7) was a factor higher than for that of the Inco data (Figures 4 and 5). Therefore, although it was possible to discriminate between treatment conditions in terms of water quality with the Stanrock and Inco datasets, water

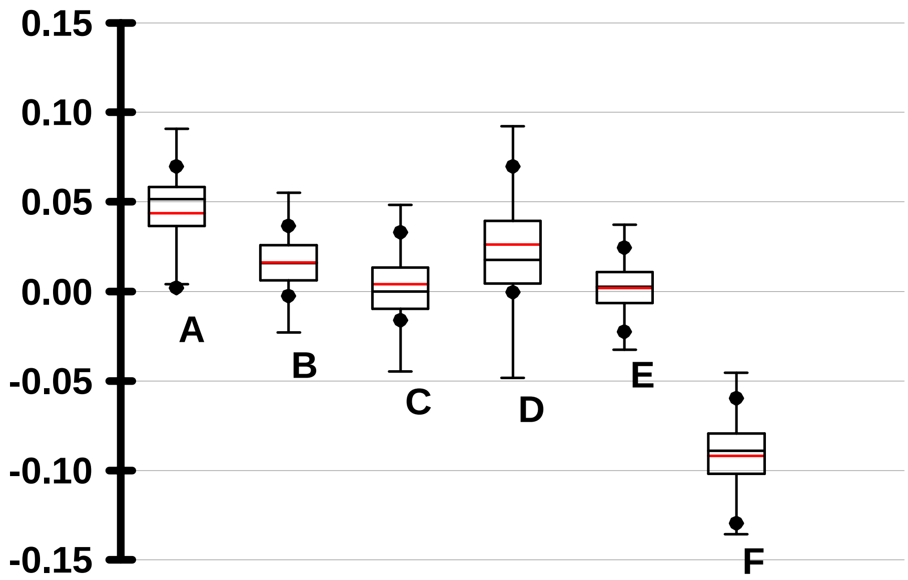

Figure 4. Respective scaled discriminant scores based on the first canonical component (94% variability)of the Inco data at a depth of 7.5 cm. Data at this depth were grouped by treatment conditions, A to F as indicated. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors.

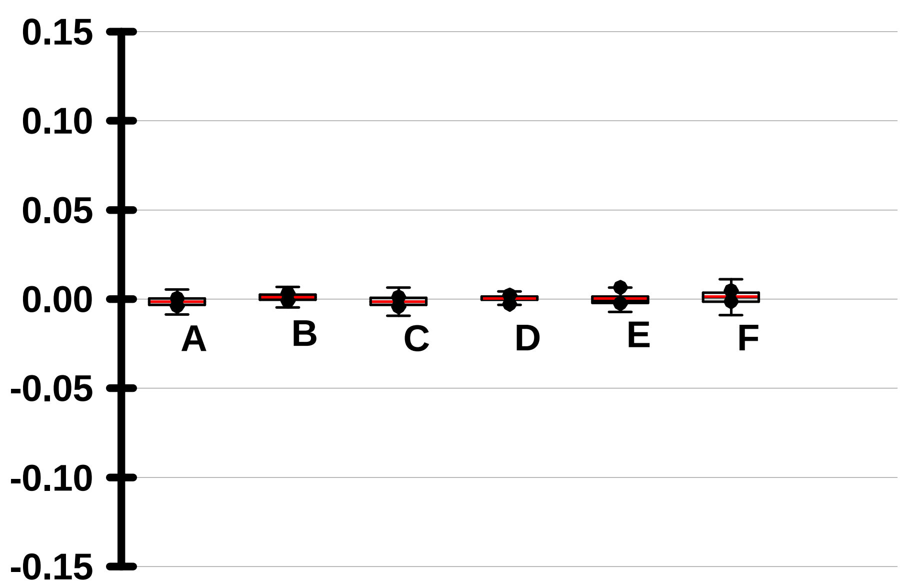

Figure 5. Respective scaled discriminant scores based on the first canonical component (95% variability)of the Inco data at a depth of 22.5 cm. Data at this depth were grouped by treatment conditions, A to F as indicated. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors.

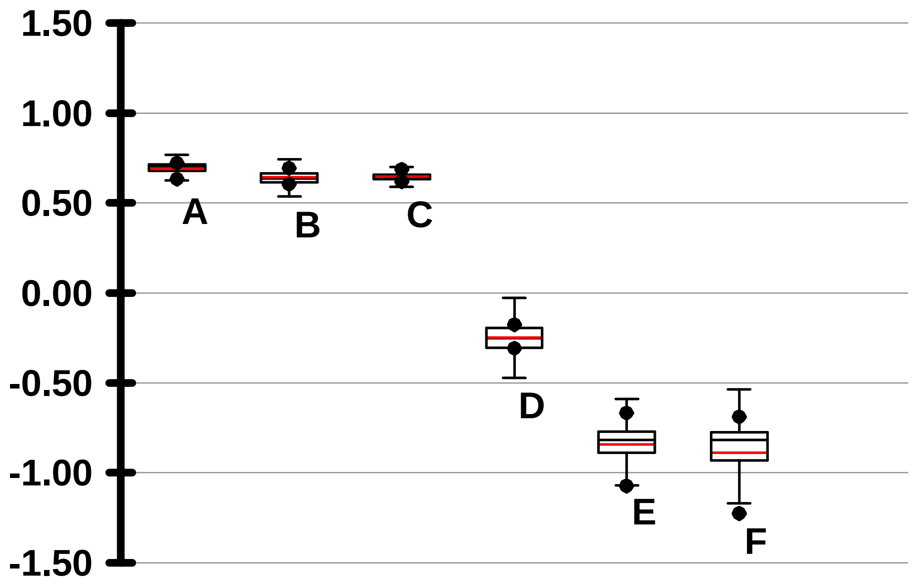

Figure 6. Respective scaled discriminant scores based on the first canonical component (99% variability)of the Stanrock data at a depth of 7.5 cm. Data at this depth were grouped by treatment conditions, A to F as indicated. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors.

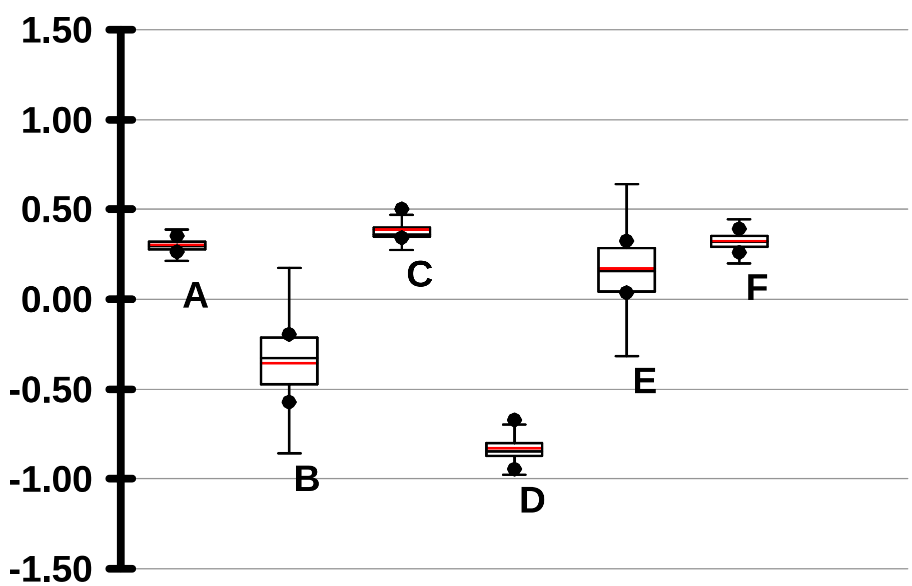

Figure 7. Respective scaled discriminant scores based on the first canonical component (98% variability)of the Stanrock data at a depth of 22.5 cm. Data at this depth were grouped by treatment conditions, A to F as indicated. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors.

qualities between the treatments for the Inco experiment would appear to have been considerably more similar.

Further inspection of Figures 4 and 5 reveals that at the second surface layer (mean depth of 22.5 cm), no impact of treatment is observable. However, the compositional analysis indicates that Inco treatment F did generate distinct water quality conditions, but only in the upper surface layer (mean depth 7.5 cm). Logcontrast canonical component analysis comparing water qualities between these two depths for the respective Inco treatments (Figure 8), further supports the fact that only the upper surface layer in treatment F was distinct. Additional evidence for the finding that treatment impacted only the surface layer was generated by comparing Inco treatment F at all three measured depths, 7.5, 22.5 and 65.0 cm, respectively (Figure 9).

For the Stanrock treatments in the upper surface layer (Figure 6), treatments E (high phosphate rock) and F (high horse manure and high phosphate rock) would appear to have exerted

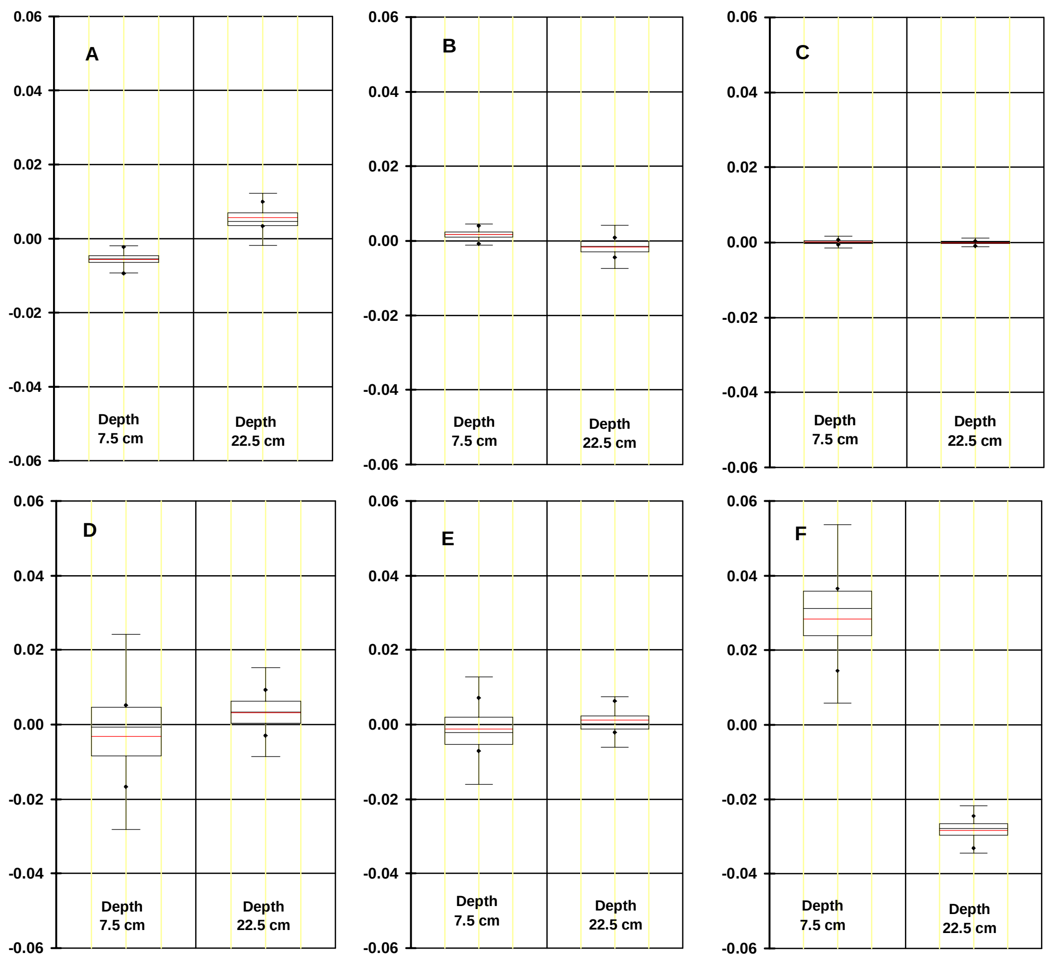

Figure 8. Respective scaled discriminant scores between water quality compositions at depths of 7.5 and 22.5 cm for treatments A to F for the Inco data. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors. Treatment F resulted in the greatest depth impacts on water quality. Treatments D and E at a depth of 7.5 cm exhibit the highest degree of variability for the samples taken over time.

a similar influence on water quality. An intermediate level of impact is suggested for Stanrock treatment D (high horse manure and low phosphate rock). However, the impact of the Stanrock treatments on water quality within the second surface layer (Figure 7) does not exhibit the same coherent trend.

A comparison of water qualities between the two upper surface layers for the Stanrock data (Figure 10) suggests that a relatively distinct upper surface layer effect (presumably from treatment) can only be observed for treatments E and F. The fact that Stanrock treatment D does not show significant depth dependence in Figure 10, but can be discriminated in Figure 7 could suggest that treatment was more than just a surface phenomenon in this one case. This interpretation is questionable or at least contradicted to some extent by the fact that Stanrock treatment B was not discriminated in the surface (Figure 6), nor between surface layers (Figure 9), but was distinct with respect to the other treatments in the subsurface (Figure 7). Logcontrast canonical component analysis of the Stanrock treatments contrasting both treatment and depth together indicates that at least for treatment D the impact on water quality was more than just a surface phenomenon (Figure 11).

From the box plots presented in Figures 4 and 6, it can be seen that the level of variability in water qualities for samples taken over time within a given treatment were of a similar order of magnitude at the Inco site (Figure 4), but were somewhat treatment dependent for the Stanrock site (Figure 6). If the impact of treatment on water quality was essentially an upper surface layer phenomenon, then it would be of interest to determine the extent to which the exhibited water quality variability in that layer was related to temporal change and to examine if the respective water qualities were at all convergent or divergent in time.

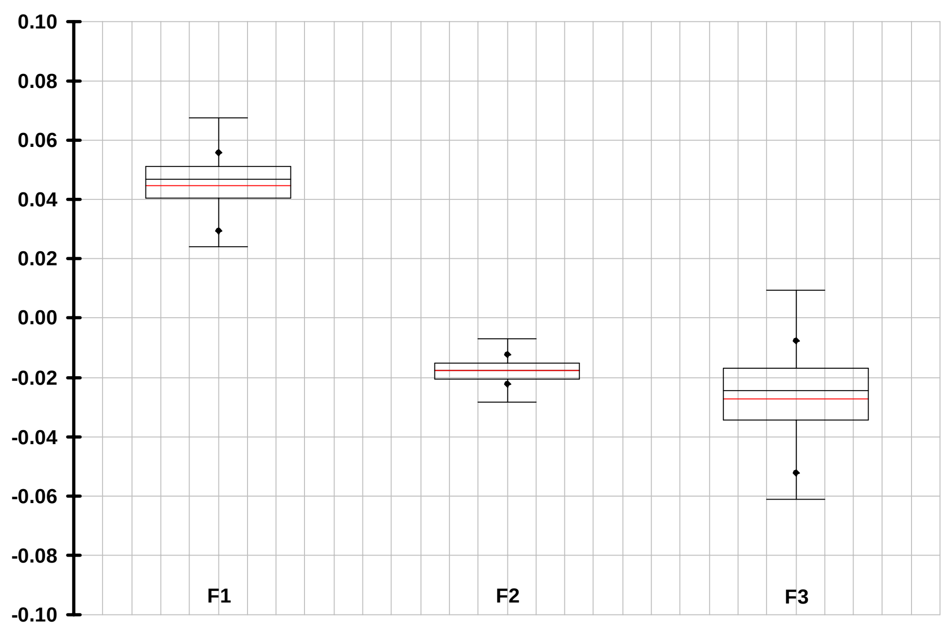

Figure 9. Respective scaled discriminant scores between water quality compositions at depths of 7.5 (1) 22.5 (2) and 65.0 (3) cm for treatment F for the Inco data. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors.

Since treatment F exhibited a significant impact on water quality at both sights, the question of time dependence was addressed by contrasting treatment A with F within the upper surface layer (Figure 12). This analysis indicated that from the onset the water quality resulting from Inco treatment F was more similar but slightly divergent in time with respect to the control. The Stanrock treatment F produced a relatively more distinct and stable water quality with respect to the control.

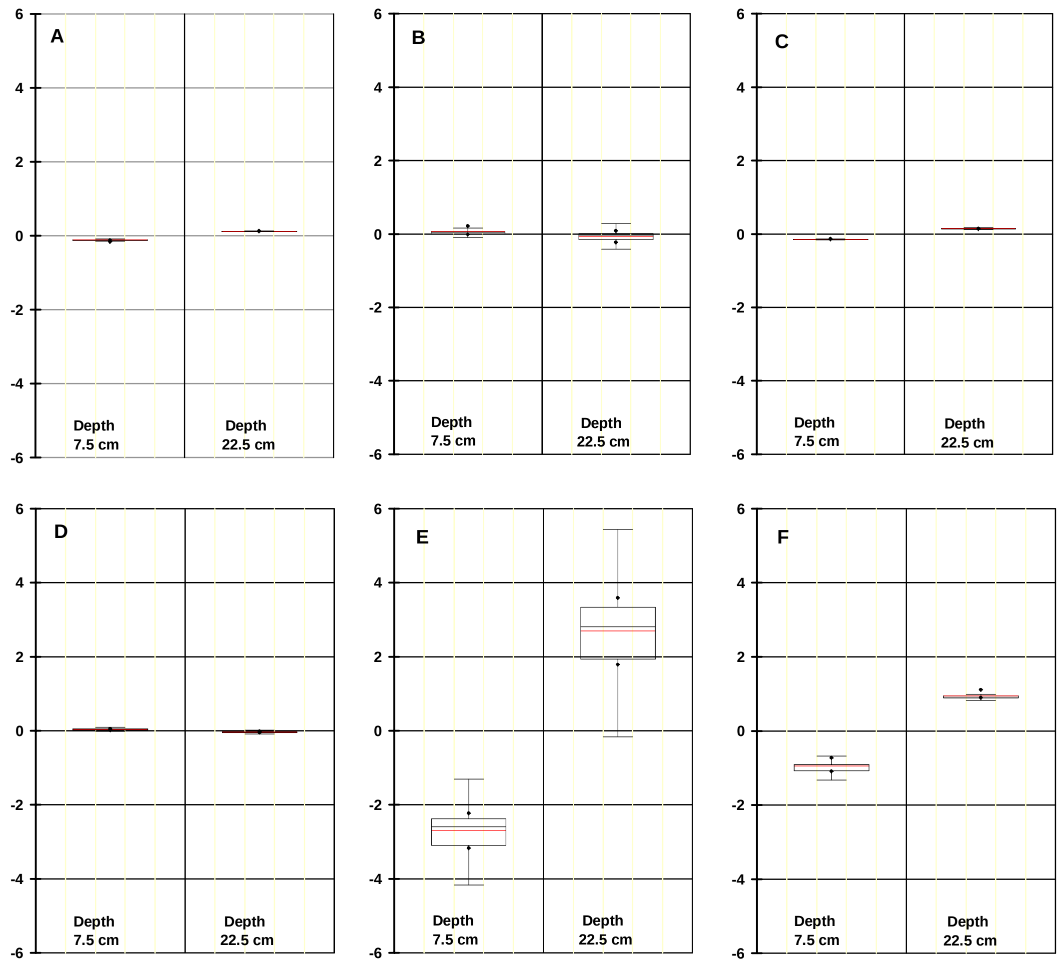

Figure 10. Respective scaled discriminant scores between water quality compositions at depths of 7.5 and 22.5 cm for treatments A to F for the Stanrock data. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors. Treatments E and F resulted in the greatest depth impacts on water quality. Treatment E exhibits the highest degree of variability for the samples taken over time.

Conclusions:

Compositional analysis of water quality data obtained during the monitoring of phosphate rock and horse manure amendments at the Inco and Stanrock mine tailings sights indicates the following:

1. Treatment had a greater impact on water quality at the Stanrock test site.
2. Treatment F (high horse manure and high phosphate rock) appears to have exhibited the greatest impact on water quality with respect to the experimental control (Treatment A) over the monitoring period.
3. With the exception of Stanrock treatment D, treatment resulted essentially in a change in only the upper surface water quality with respect to the control.

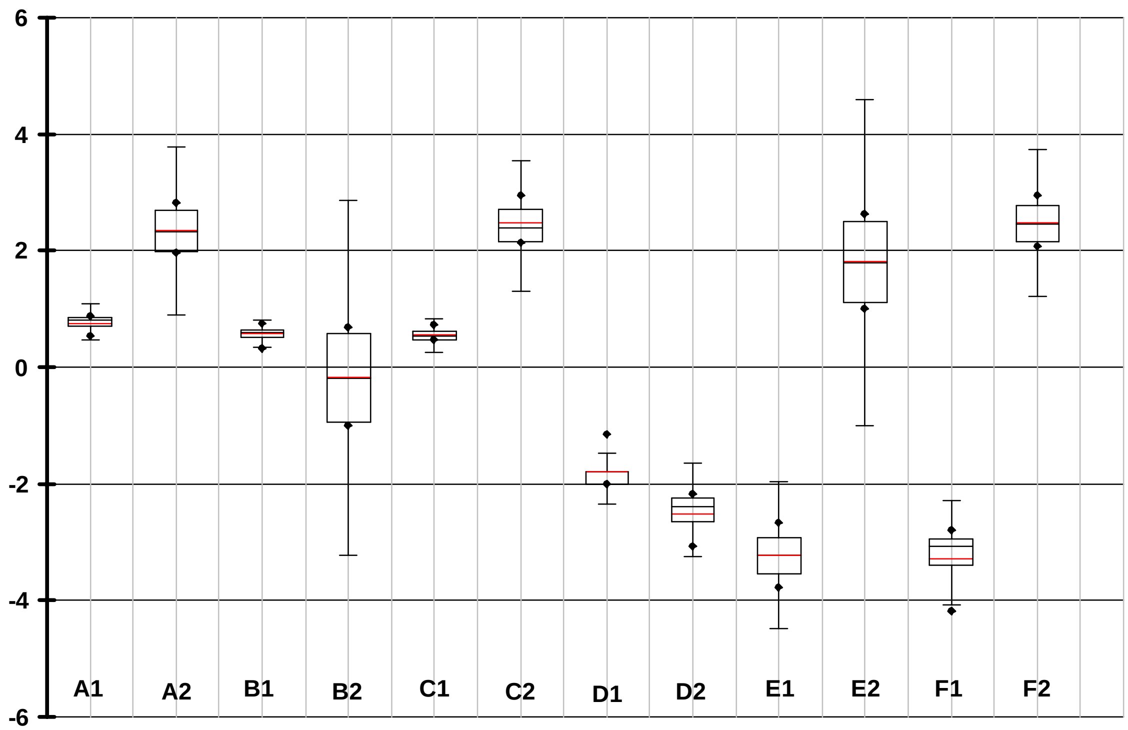

Figure 11. Respective scaled discriminant scores between water quality compositions at depths of 7.5 (1) and 22.5 (2) cm for treatments A to F (Table 1) for the Stanrock data. Within group variability illustrated by the box plots represents a combination of measurement and temporal factors.

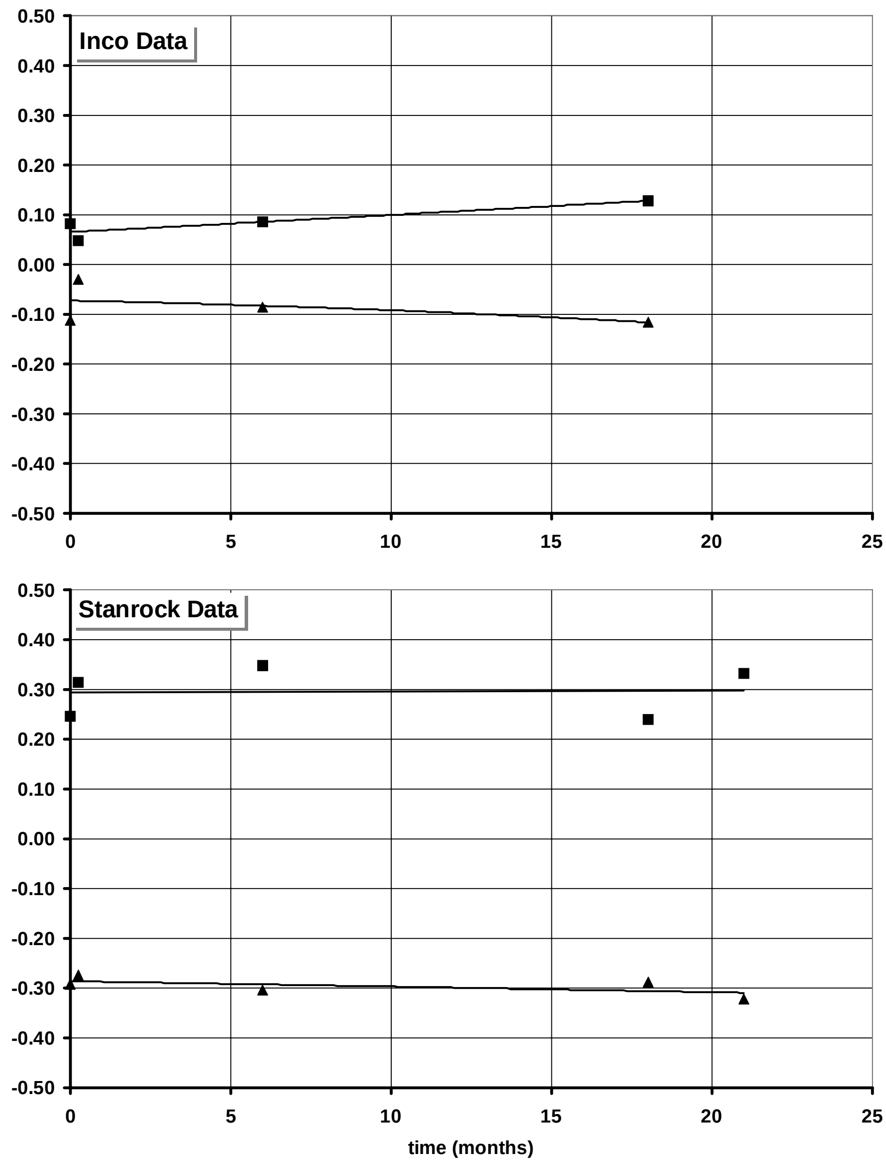

Figure 12. Scaled discriminant scores as a function of time obtained from Logcontrast canonical component analysis contrasting treatment A (Control—▲) and F (High horse manure and high phosphate rock—■) for the Inco and Stanrock sites as indicated.