Assessing the soil quality of long-term reclaimed wastewater-irrigated cropland - Principal component and factor analysis

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Abstract

The properties of soils may be characterized by many attributes. However, there is not a systematic procedure to objectively select the measurement parameters that may be used to assess soil quality. Following the data collection, it is often a dilemma to decide how many and which of the measured parameters should be included in the assessment as the outcomes may be influenced by the parameters included. In this study, 29 physical, chemical, and biological attributes of soils at a long-term reclaimed wastewater irrigated field in Bakersfield, California and its adjacent non-wastewater irrigated control were determined with samples collected along a 100 m transect at 1 m interval. The fields have been cultivated with varieties of field crops over the past 70 years. The spatial variability of the data was evaluated. The principal component method was employed to identify the soil attributes that were most significant in describing variances of the fields. Soil quality of the treated and control fields were compared using the principal components identified in this process. Results indicated that the soil quality might be evaluated by comparing the total porosity (or drainable porosity), pH, electrical conductivity, magnesium (Mg), phosphorus (P), and zinc (Zn) of soils in the control and the treated fields. Except for the total porosity and Mg, the other soil parameters of the control and treated fields were not significantly different. While the soils of both fields support successful crop production, the reclaimed wastewater irrigation appeared to slightly increase the soil compaction and reduce the soil's capacity of holding nutrient elements, such as Mg.

Keywords: spatial variability; soil quality; spectral analysis; principal component and factor analysis

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1. **Introduction**

Historically, the quality of soil has been judged primarily on its suitability for an intended use (Hillel, 1991). The ability of soil to sustain crop production is perhaps the oldest and the most commonly used criteria to judge soil quality (Warkentin, 1995). Soil is the medium that supports plant growth, and modulates water, nutrients and pollutants transport in the terrestrial environment. It also serves important ecological functions in sustaining a diverse and dynamic microbial community, cycling of biochemically essential elements, being the major sink for global atmospheric fallout of trace elements and toxic organic chemicals, and being the ultimate receptor of wastes. Logically, the connotations of soil quality should include environmental sustainability (Haberern, 1992; Doran and Parkins, 1994). Soil quality therefore must measure the capacity of soil to support ecosystem functions, to sustain biological productivity, to maintain environmental quality, and to promote plant, animal and human health.

Larson and Pierce (1991) outlined five major soil functions that may be used as criteria for judging soil quality, namely ability to hold, accept, and release water to plants, streams, and subsoil (water flux), ability to hold, accept, and release nutrients and other chemicals (nutrients and chemical fluxes), promote and sustain root growth, maintain suitable soil biotic habitats, and respond to management and resist degradation. Doran and Parkin (1996) suggested that, for practical purpose, soil quality be judged on soil's impacts on crop yields, erosion, ground water quality, surface water quality, air quality, and food quality (Karlen and Stott, 1994; Regannold and Palmer, 1995). If a set of attributes is selected to represent the soil functions and if appropriate measurements are made, the data may be used to elaborate the soil quality (Heil and Sposito, 1997). Soil quality evaluation often includes a large-scale and multiple-attribute field survey. In addition to the selection of measurement parameters, issues concerning spatial variability of the field must also be factored into the investigation (Wendroth et al., 1997). The basic soil attributes selected and the processes they represented not only need to indicate these soil functions but also need to account for the variability of the fields.

In this study, we examined the statistical characteristics and the internal relations of 29 soil attributes of samples obtained from a long-term reclaimed wastewater irrigated field and its no-treatment control and demonstrated the utility of the principal component and factor analysis method in selecting the most-appropriate and minimal parameters for evaluating the soil quality.

2. **Materials and Methods**

2.1. Sites and samples

Two crop production fields in Bakersfield, California were selected for this investigation. The first field, designated as the treated field, was inside the 2000+ hectares municipal farm that have been continuously cultivated and under reclaimed municipal wastewater irrigation for over 80 years (N 35^{o}18'05", 118^{o}57'33''). Treated wastewater from the City of Bakersfield that was stored in reservoirs were used to fulfill the seasonal demand of irrigation for barley (*Hordeum vulgare*), corn (*Zea mays*), cotton (*Gossypium hirsutum*), alfalfa (*Medicago sativa*), and sorghum (*Sorghum vulgare*). On the average, approximately 1.4 m of reclaimed wastewater has been applied annually. During this period of time, the wastewater collection and treatment system has continuously evolved in response to the growth of the city and the regulatory requirements. As inflows and out flows of the reservoirs dynamically fluctuated with supplies and demands, there was no record on the chemical characteristics of the applied water. Typically, reclaimed wastewater contains 10 – 20, 5 – 15, and 5 - 10 mg l^{1} of biochemical oxygen demand (BOD), total nitrogen, and total phosphorus, respectively (Pettygrove and Asano, 1985; Tchobanoglous and Burton, 1991). Through municipal uses, the total dissolved solids of the treated water may increase from 150 – 380 mg l^{-1}. The treated fields represented the conditions of soils that have been under the low intensity, long-term enhanced influences of nutrients, salinity, and potential pollutants present reclaimed wastewater. The second field, considered as the control field, located diagonally adjacent to the treated field (N 35°17'42", 118°57'53"). It had been cultivated for approximately equal length of time with similar crops using water from the same source as the City of Bakersfield.

Soils in these two fields were sampled in September of 1998, at the end of growing season. Soil samples were taken at 1-m intervals along a 100-m transect that was perpendicular to the direction of irrigation furrows and was approximately 150 m down field from heads of furrows. The beginning and ending points of transect were >>150 m from edge of the field. One hundred soil samples were taken at 1-m intervals along the established transect. Side-by-side undisturbed soil cores and disturbed soil samples were obtained at 0 - 15 cm soil depth at the midpoint between the furrow and the ridge. Adequate amount of bulk soils was obtained and subdivided for different types of measurements. The undisturbed cores for measurements of physical properties were taken with 5 cm (inside diameter) x 5 cm (height) brass rings. For measuring the soil respiration rates, the undisturbed cores were 5 cm (inside diameter) x 7.5 cm (height). After the extraction, soil samples were preserved in ice packed coolers until they were transferred to and stored in a 1 °C cold room at field moisture content until time for determinations. The fields were sampled in the same manner two additional times at the beginning and end of the following growing season.

2.2. Soil attributes

A total of 29 attributes of the soils were determined. These attributes reflect the soil's function to: (1) hold, accept, and release water, nutrients and pollutants to plants, surface water bodies, and subsoil; (2) maintain suitable soil biotic habitat; and (3) respond to management practice and resist soil degradation.

2.2.1. Physical attributes

Eleven measurements of the soil physical properties were included. They were bulk density (BD), maximum cone penetration resistance (MPR), clay content (Clay), saturated hydraulic conductivity (Ks), field water content (PW), saturation percentage (SP), total porosity (AC), field capacity (FC), permanent wilting point (PWP), available water capacity (AWC), and drainable porosity (DP). Except for MPR and Clay of the soils, measurements were made with undisturbed soil cores. Methods described in the *Methods of Soil Analysis, Part 1* were followed in sample preparation and determinations (Klute, 1986).

Briefly, the BD was measured as the oven dried weight on a unit volume of undisturbed soil core; Ks was measured with an undisturbed soil core using the constant head method, SP is the mass per mass saturated water content of the undisturbed soil core, AC was void volume calculated from bulk density and particle density of the soils, FC and PWC were determined as the moisture content of undisturbed soil core equilibrated in a pressure plate apparatus at 33 x 10^{3} and 1.5 x 10^{6} Pa, respectively; AWC was calculated as the difference of the corresponding

FC and PWP of a soil, DP corresponded to the volume of pore in which the water is gravitationally drained.

2.2.2. Chemical attributes

Fifteen soil chemical properties were measured. They included soil pH (pH), electrical conductivity (EC), organic matter content (OMC), total nitrogen (N), total carbon (C), calcium (Ca), magnesium (Mg), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), phosphorus (P) and lead (Pb) contents, and cation exchange capacity (CEC). The general procedures outlined in the *Methods of Soil Analysis, Part 3* were followed and sample preparation and determinations (Sparks et al., 1996).

The pH and EC of the soils were determined in the saturation extracts. The OMC of the soils were determined by the dichromate oxidation method. Total nitrogen and carbon contents of the soils were determined by the Dumas combustion method using Carlo-Erba NA 1500 Nitrogen Analyzer. Soils were microwave digested in aqua regia and the concentrations of dissolved Ca, Mg, Cd, Cr, Cu, Ni, Zn, P and Pb were determined by ICP-OES spectroscopy. CEC was determined by the ammonia acetate method at pH 7.

2.2.3. Biological Attributes

Three major biological properties, namely the respiration rate (CO_2), dehydrogenase activity (DEHY) and dry plant weight (DPW) were included. The method developed by Martens (1995) was followed in determining the respiration rate. The DEHY of soils were measured as release of formazan released using the 3% 2,3,5 triphenyltetrazolium chloride as the substrate (Casida 1997). The phosphorus lipid profile of soils was determined according to Zelles et al. (1992), and BIOLOG substrate metabolism profile (Zak et al., 1994) was used to measure the soil microbial activities.

2.3. Data Analysis

Descriptive statistics in the forms of mean, standard deviation, distribution normality, and skewness were determined (Wendroth et al., 1997; Pierce and Gililand, 1997). The auto-correlation function and the semi-variogram function of data collected along the 100-m transect were derived for each attribute (Knighton and Wagenet, 1987; Knighton, 1998). Subsequently, the nugget, sill, and range of the data set were determined for each attribute (Webster and Oliver, 1990; Cressie, 1991). Spectral analyses were also conducted using SAS program (Brocklebank and Dickey, 1986) to detect possible cyclic patterns corresponding to soil management practices. The cross-correlation functions were developed to evaluate the inter-relationships and inter-dependence between attributes. The principal component and factor analyses (maximum likelihood) procedures in the MINITAB software package (Release 12. MINITAB INC., 1998) were used to rank the 29 initial attributes. This analysis identified a subset of soil attributes that represented the principal factors and key variables in the system (Vekemans et al., 1989).

3. Results and Discussion

3.1. Descriptive statistics and spatial variability

The descriptive statistics of the control field, as shown in Table 1, are representative of the nature of the data in both fields. For many of the soil attributes, the measured values for samples obtained along the 100 m transects varied by orders of magnitude. Depending on the parameters, the skewness factor varied from -0.75 to 2.4. For 22 of the 30 data arrays summarized in Table 1, the skewness factor was between -1 and 1 and the data were normally distributed. The distributions of measured Ca, Cu, Ks, MPR, C, Cd, DEHY, and Mg of soils however were noticeably skewed, characterized by wide-ranging numerical values, high degree of relative data dispersion, and slightly higher mean than the median values. For example, Ks along the 100 m transect varied from 0.03 to 0.5 m s^{-1} with mean and median of 0.1 and 0.08 m s^{-1}, respectively and a coefficient of variation of 94%. A closer examination of the data set indicated that, with the exception of a few outliers toward the higher end of the range, the values for the majority of data points were rather low. As the soils were sampled at a regular interval along a 100 m transect, the dispersion of the data indicated possible presence of spatial variation on the parameters measured.

Soil properties inherently change across the landscape due to variations of the pedogenic processes or alterations caused by the cultivation practices. Measurements for a soil attribute may be spatially interrelated across the landscape as soils obtained at adjacent locations might have subjected to the same influences. To evaluate the soil quality of a field, the spatial structure of soil attributes should be considered because the spatial variations are seldom completely random. When the data were evaluated in terms of space, the data for almost all attributes were spatially structured as the results in Table 2 indicated. The Cd, Pb, Ks, MPR, and DEHY were more spatially varied with above-average deviations than CEC, pH, SP, BD, N, Mg, and P. The semivariograms suggested that there existed a range of 2 – 10 m for MPR, Clay, Ks, PW, AC, AWC), Mg, Cr, Ni, Zn, P, Pb, CO_2, DEHY, and DPW. The remaining attributes showed a wider range of 15 – 40 m. Most of the semi-variograms showed large nugget/sill ratios indicating that additional variability still existed at a scale smaller than the observation distance of 1 m. The outcomes of spatial variability analysis for the wastewater treated field were similar. It was apparent that each parameter did not vary spatially in the same manner. Therefore, it is essential that variability be accounted for in the selection of the parameters for soil quality assessment.

3.1.1. Spectral analysis

Soil physical conditions and plant growth may be affected by distance-related cyclic patterns caused by past land management practices such as wheel spacing of farm machinery, crop rotation cycles, and irrigation patterns (Nielsen et al., 1983; Kachanoski et al., 1985; Bazza et al., 1988; Nielsen and Alemi, 1989). In addition, the pedogenic processes may also cause the soil properties to gradually change over the landscape. Spectral analysis filters the progressive and recurrent variance components of a soil parameter that were caused by natural events and cultural practices in the past.

Periodograms with frequency period varying from 1 to 100 m were calculated for every soil attribute. The periodograms for all the 29 soil attributes of the control soil were crowded into one single diagram (Fig. 1) to illustrate the pattern emerging from the examining them collectively. Again, the treated field exhibited similar patterns in the distribution of variances. By and large, most of the attributes showed a noticeable cyclic pattern of variation periods less than 40 m. The values of total porosity (AC) along the transect appeared most likely to reoccur at a 4 m interval, which may have indicated soil compaction caused by wheel spacing of cultivation equipment. However, the magnitudes of the periodic effects at short distances (< 20 m) for all the attributes were very weak. At the most, the cyclic patterns of AC, as identified by the spectral analysis, accounted for 25% of the total variance. The cyclic effects for other soil attributes were much weaker as most of them accounted for less than 10% of the total variance. Variance at large distances (periods) greater than 1/3 of the total distance (100 m), although high for some attributes, are not statistically significant to explain the data patterns. The spatial structure of the observations appeared not to be caused by any identifiable or known periodic effect. The lack of significant progressive and recurrent patterns in the distribution the variances indicated that the influences of the cultural practices were not strong and outcomes of soil quality assessment based on these parameters would reflect the influence of the treatment (i.e. wastewater irrigation).

3.2 Principal components and factors

If field sampling and determinations are properly conducted, the variances of the measurements collectively indicate the treatment effects. Attributes selected for soil quality assessment ideally must account for most, if not all, of the variances observed in the measurements taken. For the 29 soil attributes measured, there exists a maximum of 29 factors that may explain the total system variance. A factor, as an array variable, holds contributions (in the form of loading or weights) from all of the 29 attributes. The total variance of each factor was defined as *eigenvalue* (Swan and Sandilands, 1995). An eigenvalue plot enables one to identify the significant factors that collectively represent major portions of the total system variance.

From the eigenvalue plot (Fig. 2) and the cumulative variance plot (Fig. 3), factors 1 through 6 are more significant in explaining the system variance than the remaining factors. The first and most important factor (factor 1) explained 20% of the total variance. Factors 1 through 6 collectively accounted for 60% of the total variance. Adding Factors 7 through 10 increased the cumulative variance to 70%. The inclusion of the next 9 factors increased the cumulative variance by approximately 5%.

The loadings (i.e. contribution) of each soil attribute toward the first and second factors are shown in Fig. 4. The loading of Zn, Mg, P, Cr, Ni, Ca and Cu to the first factor were >0.5; 12 soil attributes (C, N, pH, Clay, CEC, OMC, Cd, PWP, AC, SP, PW, DP, and FC) had lower loading, between 0 and 0.5. Other soil attributes had zero or negative contributions toward the first factor (namely, factor 1). Similarly, the second factor was positively influenced by BD and negatively influenced by C, N, Ca, Cu, SP and CEC and OMC. The loadings of the other soil attributes were largely negative.

As Factors 1 and 2 collectively explained only 32% of the system variance, it was necessary to include additional factors so that greater percentages of the total variances might be accounted for. To illustrate the complete spectrum of the system's variances that originated from each of the measured soil attributes, the loading values of each soil attribute to all the 19 factors were plotted in Fig. 5. In this diagram, the soil attributes were distributed in equaled spacing along the horizontal axis, the loading of each attribute toward a factor is indicated on the vertical scale, and a colored line was drawn linking the loadings of the same factor to show the fluctuations across the soil attributes. Notice that some soil attributes were associated with high loading values from one or several factors (i.e. loading > |0.4|), indicating their significance toward the total variance. There was also soil attributes not associated with high loading of any factor, such as Ks. The relative importance of each soil attribute, in terms of its contribution to all of the factors, is judged by its communality value, a value that indicates the residual variance of the attribute in comparison to a critical convergence value of confidence (Joreskog, 1977). If the residual variance is less than the convergence value, the corresponding communality of the attribute is equal to 1. Otherwise, its communality is less than 1. Fig. 6 shows the sorted communality values for all the 29 soil attributes of the control field. The attributes describing soil-water status, such as FC, PWP, DP, AC, and AWC appeared to be most representative of the system variance (communality = 1). These attributes were associated primarily with Factors 2, 3, 4 and 5 (Fig. 5). In the next group ($1 > \text{communality} \geq 0.9$) were C, Zn, Ca, Mg, and P that were highly representative. They were associated with Factor 1 (Fig. 5). In addition, soil attributes that had communality values between 0.8 – 0.9 were fairly representative. They included EC, Cu and pH. Soil attributes with low communality values ($0.6 < \text{communality} < 0.8$) were OMC, SP, Cr, BD, N, CEC, Ks and Ni.

The biological attributes, dry plant weight (DPW), dehydrogenate activity (DEHY) and soil respiration rate (CO_2) did not appear to contribute significantly toward the total variance and were among the five attributes of the lowest communality values. The least interrelated attribute to others was the maximum cone penetration resistance (MPR).

3.3. Minimum data sets

For soil quality assessment, a minimum data set (MDS) should be composed of soil attributes that account for majority of the variances. This data set will have the smallest possible number of soil attributes for a practical assessment. Larson and Pierce (1994) elicited that the minimum data set included the key soil attributes that are representative of other attributes and were sensitive to major soil functions. Ideally, the selected attributes should be easily measured and the measurements are reproducible and standardized.

Alternative to the use of communality values, the correlation matrix of the factor analysis may be used to objectively select the appropriate soil attributes and factors based on a selection criterion. With the individual loading values (as the matrix components), a loading limit, L, may be preset at different levels as a bar criterion. Factors containing soil attributes with loading values greater than L are selected into a temporary MDS. The remaining is not considered significant or representative of the system. As the L value increases, the number of selected factors and attributes drop.

For the data set from the control field, setting the loading limit at $L = 0.5$ resulted in twelve selected factors, as shown in the upper chart of Fig. 7. Almost all attributes, with the exception of Ks, Cd, CEC, and DPW, were included in this MDS, as shown in the lower chart of Fig. 7. When L was increased to 0.6, eight factors (1 through 5, 7 through 9) were selected and 20 soil attributes appeared in the resulting MDS (Fig. 8). The number of attributes in the MDS was reduced to 13 and 10, when $L = 0.7$ and 0.8, respectively (Figs. 9 and 10). For $L = 0.9$ (Fig. 11), the resulting MDS consisted of only 5 attributes, namely, available water content (AWC), drainage porosity (DP), magnesium (Mg), zinc (Zn) and phosphorous (P).

The above procedure and analysis were applied to the data obtained from the treated field. A comparison of the final selection of the attributes, corresponding to a common loading limit of $L = 0.85$, is shown in Fig. 12. The treated field had 6 representatives (AC, PWP, AWC, DP, Zn, and P) while the control field had 8 (AC, FC, AWC, DP, pH, EC, and Mg). It appeared that much of the variance in both the control and the reclaimed wastewater treated fields originated from the variations in the soil physical attributes. Soil attributes representing the biological characteristics did not vary significantly and they did not make the list of the minimum data set. The soil attributes measuring the physical properties of the soils are mathematically interrelated that AC = FC + DP = (PWP +AWC) + DP. These parameters may be consolidated and represented by AC and DP (or FC). The characteristic representatives of each field may be reduced. They are AC, DP, Zn and P for the reclaimed wastewater irrigated (treated) field, and AC, DP, pH, EC, and Mg for the control field.

3.4 Soil quality assessment

The combining the MDS of the control and the treated fields yields the parameters (AC, DP, pH, EC, Mg, P, and Zn) through which the soil quality of the reclaimed wastewater irrigated field and the control field may be compared. Fig. 13 summarizes the graphic comparisons of AC, DP, pH, Mg, P, and Zn between the reclaimed wastewater treated and the control fields.

These parameters are the reasonable indicators for the soil quality of reclaimed wastewater irrigated fields. The soil total porosity (AC) and the drainage porosity (DP) reflect soil's ability to absorb and release water. They represent the soil's fundamental characteristics that affect soil physical properties such as hydraulic conductivity and bulk density, and are affected by others inherent soil properties such as Clay, OMC, MRP, etc. As the control and treated fields are adjacent to one another and have the similar soil texture, AC and DP will be indicative of the cultivation practices.

The pH and EC of the soils are indicators of the background chemical matrices of the soils and they may be over the long run affected by the cultural practices, water quality, and fertilizer inputs. The Ca and Mg contents of the soil usually are indicative of the soil cation exchange capacity that is fundamental in determining the soil's ability to retain and release nutrients, including trace elements. In irrigated soils, the Ca content may not be clearly distinguished as Ca is a prevalent cation in the irrigation water and the receiving soil is expected to contain abundant Ca on the exchange complex and as precipitates. As a result, Mg, in this case, will be a reasonable substitution, as Mg chemically interacts in proportion with Ca. Comparing to the source water, the reclaimed wastewater is expected to contain higher concentrations of P and Zn. They are representatives of residual pollutants in the reclaimed wastewater. Long-term reclaimed wastewater application may introduce significant amounts of P and Zn into the receiving soil.

The soil quality differences between the treated and control fields, as measured by these parameters were relatively minor. All of their values were well within the ranges that were typical for cropland soils and were suitable for sustaining crop production. Only the AC and Mg of the two fields are significantly different ($p < 0.05$). Both the AC and Mg of the control field were higher than those in the reclaimed wastewater-treated field. It appeared that the long-term reclaimed waster irrigation has slightly increased the soil compaction, as the AC of the treated field was significantly lower than that of the control. The physical attributes represented by AC (DC, FC, PWP, and AWP) would be affected accordingly. The lower Mg content of the reclaimed wastewater irrigated field may be an indication that the ability of the soil in retaining nutrients is lower. Indicators of pollutant accumulation in the soils, P and Zn, were not significantly different between the control and treated fields. It suggests that reclaimed wastewater irrigation does not result in pollutant accumulation in the receiving soil.

4. Summary and Conclusions

Many soil attributes may be employed to assess the soil quality. There is not a standardized and objective procedure to identify the necessary parameters. Following the data collection, it is a dilemma that how many of the measured factors should be included in the assessment as several parameters may result in conflicting interpretations. In this study, 29 physical, chemical, and biological attributes of soils at a long-term reclaimed wastewater irrigated field in Bakersfield, California and an adjacent non-wastewater irrigated control field were determined with samples collected along a 100 m transect at 1 m interval. The two fields had been cultivated with varieties of field crops over the past 70 years. The spatial variability of the data was evaluated, the principal component method was employed to identify the soil attributes that are most significant in describing the variance of the fields, and soil quality of the treated and control fields was compared. It was found that:

- The majority of the soil attribute values followed a normal distribution with relatively narrow data dispersion. Values of saturated hydraulic conductivity (Ks), maximum cone penetration resistance (MPR), organic C, Ca, Mg, Cu and Cd contents of the soil and dehydrogenase activity (DEHY) were noticeably skewed. The skewness was characterized by wide ranges between minimum and maximum values, means slightly larger than medians, and small number of extreme outliers distributed among observations in a narrow range. As the samples were collected spatially, the dispersion of the data was indicative of possible spatial variability of the field.
- All of the soil attributes were more or less spatially structured. For the majority of soil quality attributes, semivariograms indicated interdependency of the data with ranges of 10 – 15 m. Based on the cross correlation analyses and spectral analyses, there was not strong cross correlations among the 29 attributes and cyclic effects along the soil sampling transects. The spatially varied distribution of the data indicated that spatial variability should be accounted for in the selection of soil attributes for soil quality assessment.
- A minimum data set (MDS) was identified through factor/principal analysis. Soil porosity (AC), drainage capacity (DP), pH, EC, Mg, Zn and P may be used to describe the variances of the treated and the control fields.
- Comparing to soils of the non-reclaimed wastewater irrigated control field, the soil quality of the long-term reclaimed wastewater irrigated field was only significantly different in their total porosity and Mg content. The total porosity and Mg contents of the control soil were significantly higher than the reclaimed wastewater treated field. While soils in both fields are judged suitable for crop production, the long-term wastewater irrigation appeared to result in a slight increase in the compaction of the receiving soil and reduction in capacity of holding nutrients.

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Table 1. Descriptive Statistics of Measured Soil Quality Attributes.

Soil Attributes	Symbol	Unit	Descriptive Statistics				CV (%)	Skewness
			Minimum	Maximum	Mean	Medium		
Bulk Density	**BD**	g.cm^{-3}	1.01	1.33	1.13	1.12	7	0.52
Max Cone Penetration Resistance	**MPR**	Mpa	0.69	4.74	1.76	1.68	35	1.56
Clay Content	**Clay**	g.g^{-1}	0.09	0.19	0.14	0.14	15	0.07
Saturated Hydraulic Conductivity	**Ks**	m.s^{-1}	0.003	0.51	0.10	0.08	94	1.65
Present Field Water Content	**PW**	cm^{3}.cm^{-3}	0.08	0.33	0.25	0.25	19	-0.49
Saturation Percentage	**SP**	g.g^{-1}	0.37	0.46	0.41	0.41	5	0.36
Total Porosity (or Air Capacity)	**AC**	cm^{3}.cm^{-3}	0.37	0.55	0.46	0.47	8	-0.28
Field water-holding Capacity	**FC**	cm^{3}.cm^{-3}	0.13	0.3	0.22	0.22	11	-0.21
Permanent Wilting Point	**PWP**	cm^{3}.cm^{-3}	0.06	0.25	0.16	0.16	19	0.18
Available Water Capacity	**AWC**	cm^{3}.cm^{-3}	0.02	0.13	0.06	0.07	29	-0.08
Drainage Porosity	**DP**	cm^{3}.cm^{-3}	0.17	0.29	0.24	0.24	14	-0.13
pH	**pH**		6.86	7.68	7.36	7.41	3	-0.75
Electrical Conductivity	**EC**	mS.cm^{-1}	0.85	2.8	1.57	1.43	31	0.89
Organic Matter Content	**OMC**	%	13	19	15	15	0.1	0.58
Nitrogen Content	**N**	g.g^{-1}	0.03	0.05	0.04	0.04	9	-0.37
Total Carbon Content	**C**	g.g^{-1}	0.008	0.015	0.01	0.009	15	1.56
Calcium Content	**Ca**	g.g^{-1}	0.001	0.001	0.00	0.001	7	0.31
Magnesium Content	**Mg**	mg kg^{-1}	722	1063	862	855	10	0.42
Cadmium Content	**Cd**	mg kg^{-1}	6241	18849	8749	8123	28	2.40
Chromium Content	**Cr**	mg kg^{-1}	5886	8585	6758	6600	9	0.76
Copper Content	**Cu**	mg kg^{-1}	0.000	2.6	0.43	0.17	127	1.46
Nickel Content	**Ni**	mg kg^{-1}	13	25	18	18	13	0.46
Zinc Content	**Zn**	mg kg^{-1}	13	52	21	19	28	1.89
Phosphorus Content	**P**	mg kg^{-1}	11	23	16	16	14	0.69
Lead Content	**Pb**	mg kg^{-1}	59	99	71	71	10	0.82
Cation Exchange Capacity	**CEC**	mg kg^{-1}	0.000	21	8	7	65	0.24
Respiration Rate	**CO_2**	mg g^{-1} day^{-1}	0.007	0.03	0.02	0.02	26	0.67
Dehydrogenase Activity	**DEHY**	µg g^{-1} day^{-1}	15	93	37	36	33	1.17
Dry Plant Weight	**DPW**	g.plant^{-1}	39	139	76	76	22	0.50

Table 2. Spatial Properties of Soil Attributes.

Soil Attributes	Symbol	Range (m)	Nugget	Sill	Nugget / Sill Ratio
Bulk Density	**BD**	15	2.50E-03	6.20E-03	0.40
Max Cone Penetration Resistance	**MPR**	2	3.00E-01	3.80E-01	0.79
Clay Content	**Clay**	7	2.50E-04	4.50E-04	0.56
Saturated Hydraulic Conductivity	**Ks**	7	6.50E-03	1.10E-02	0.59
Present Field Water Content	**PW**	8	1.00E-03	2.00E-03	0.5
Saturation Percentage	**SP**	19.5	1.00E-04	4.00E-04	0.25
Total porosity (or Air capacity)	**AC**	3	n/a	n/a	
Field water-holding Capacity	**FC**	20	3.50E-04	6.00E-04	0.58
Permanent Wilting Point	**PWP**	20	5.00E-04	9.00E-04	0.56
Available Water Capacity	**AWC**	10	2.50E-04	3.30E-04	0.76
Drainage Porosity	**DP**	n/a	n/a	n/a	
pH	**pH**	15	0.01	0.06	0.17
Electrical Conductivity	**EC**	20	0.1	0.4	0.25
Organic Matter Content	**OMC**	18	3.00E-06	1.80E-05	0.17
Nitrogen Content	**N**	30	2.00E-09	5.50E-09	0.36
Carbon Content	**C**	n/a	0	2.00E-06	0
Calcium Content	**Ca**	n/a	n/a	n/a	
Magnesium Content	**Mg**	7	2.00E+05	3.50E+05	0.57
Cadmium Content	**Cd**	20	0.2	0.3	0.67
Chromium Content	**Cr**	10	3	5	0.6
Copper Content	**Cu**	n/a	7	45	0.16
Nickel Content	**Ni**	10	4	4.5	0.89
Zinc Content	**Zn**	8	25	50	0.5
Phosphorus Content	**P**	10	4000	6000	0.66
Lead Content	**Pb**	8	15	18	0.83
Cation Exchange Capacity	**CEC**	20	0.25	2.5	0.1
Respiration Rate	**CO_2**	0	1.4E-05	2.0E-05	0.7
Dehydrogenase Activity	**DEHY**	10	110	130	0.85
Dry Plant Weight	**DPW**	8	200	270	0.74

Notations of figures:

Fig. 1. Spectral periodograms for 29 measured soil attributes of the control field (Symbols are as defined in Table 1).

Fig. 2. Eigenvalue plot for 19 potential factors in the system.

Fig. 3. Relative variance represented by 19 potential factors.

Fig. 4. Loading plot indicating associations of soil attributes to Factors 1 and 2 (Symbols are as defined in Table 1).

Fig. 5. Loading plot indicating associations of 29 soil attributes to 19 factors (Symbols are as defined in Table 1).

Fig. 6. Communality values for 29 measured soil attributes (Symbols are as defined in Table 1).

Fig. 7. Factors and associated soil attributes constitute the minimum data set (MDS) with loading limit, L = 0.5. The upper chart shows the stacked attribute loading in each factor, and the lower chart shows distribution of selected attributes. (Symbols are as defined in Table 1).

Fig. 8. Factors and associated soil attributes constitute the minimum data set (MDS) with loading limit, L = 0.6 (Symbols are as defined in Table 1).

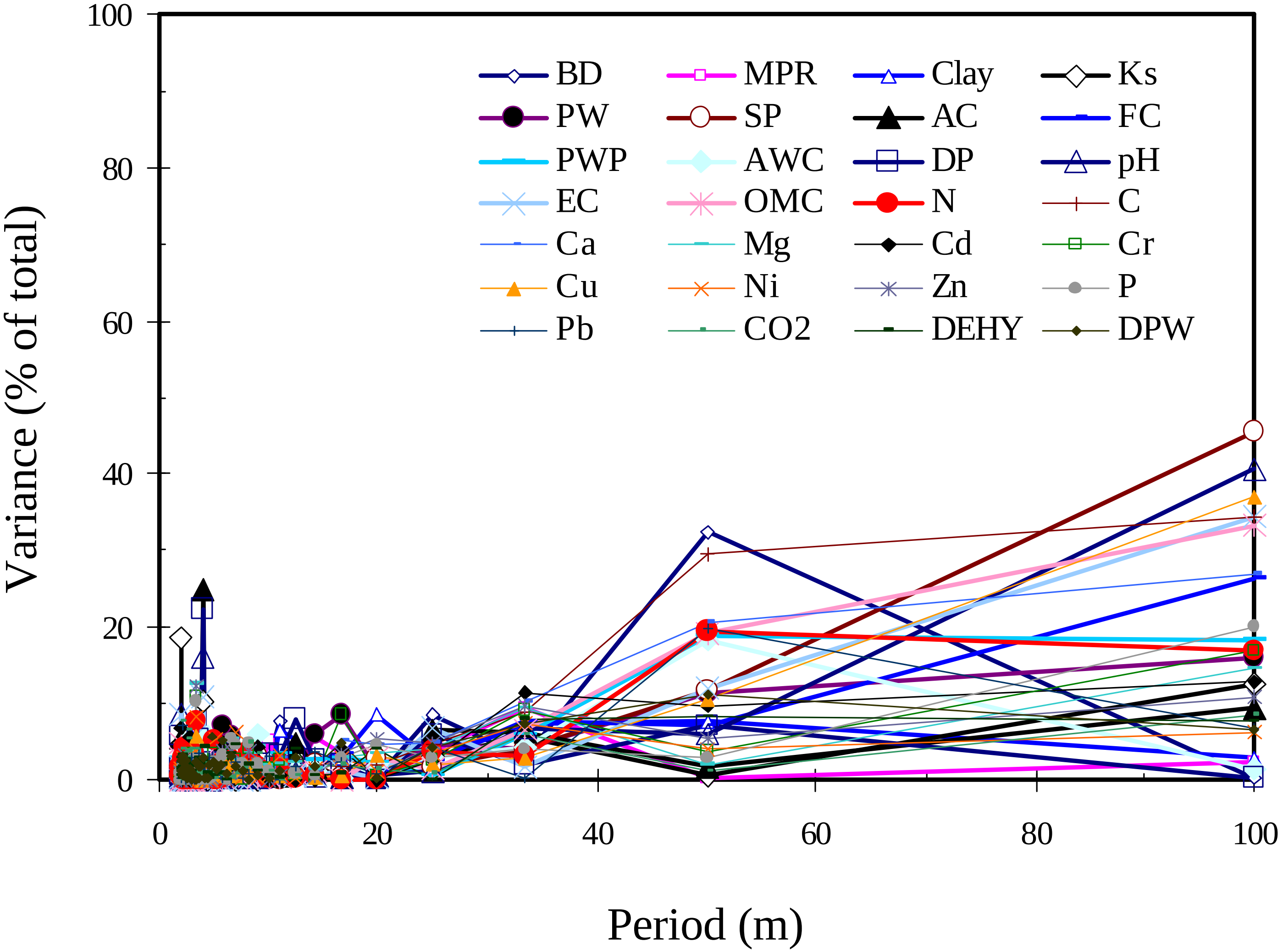
Fig. 9. Factors and associated soil attributes constitute the minimum data set (MDS) with loading limit, L = 0.7 (Symbols are as defined in Table 1).

Fig. 10. Factors and associated soil attributes constitute the minimum data set (MDS) with loading limit, L = 0.8 (Symbols are as defined in Table 1).

Fig. 11. Factors and associated soil attributes constitute the minimum data set (MDS) with loading limit, L = 0.9 (Symbols are as defined in Table 1).

Fig. 12. Soil attributes that contribute most significantly to the variances of the control and the reclaimed wastewater treated fields.

Fig. 13. Comparison of soil porosity (AC), drainage capacity (DP), pH, EC, Mg, Zn and P of the control and the reclaimed wastewater treated fields (units for each parameter is identified in Table 1).


Variance (% of total)
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80
60
40
20
0
0
20
40
60
80
100
Period (m)
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
C
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CO2
DEHY
DPW

Fig. 1

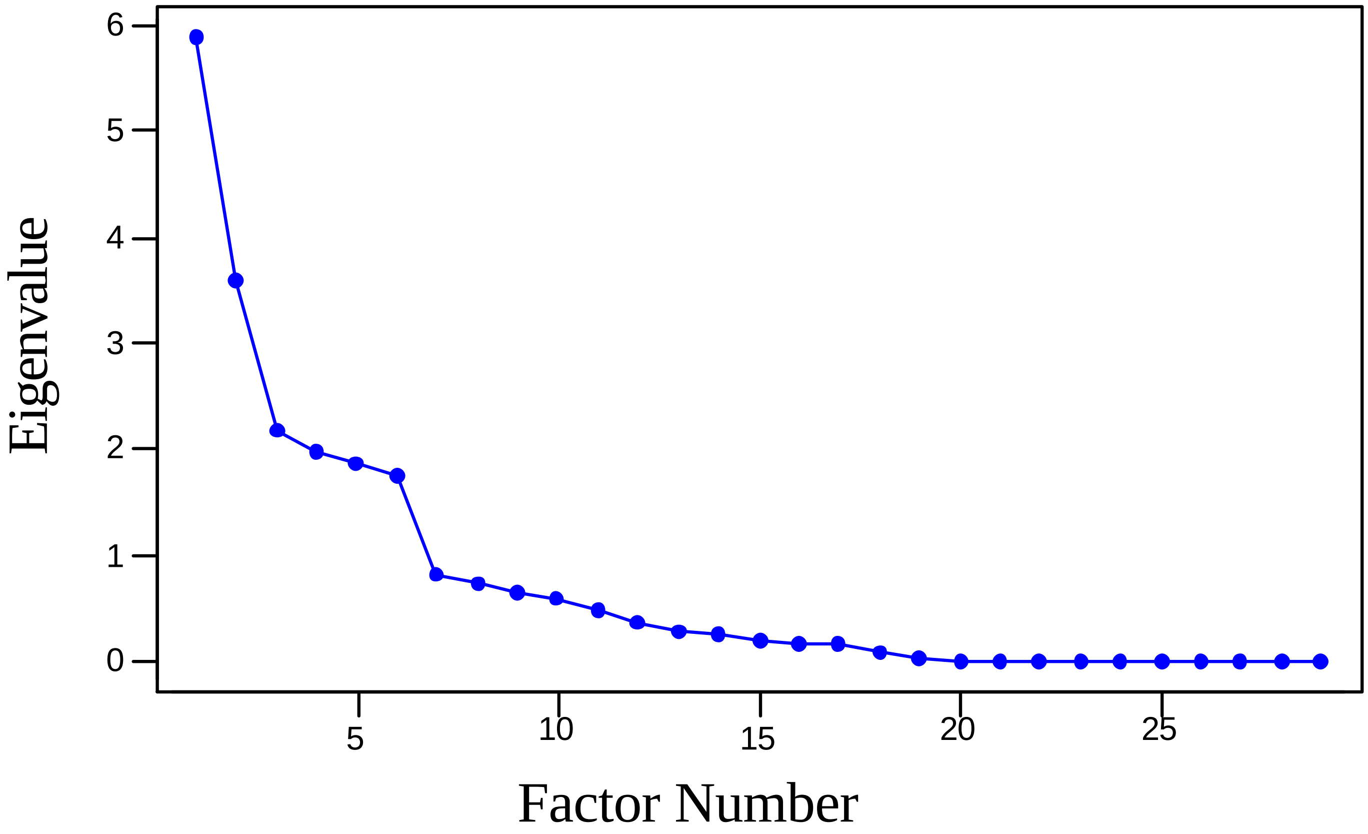


Fig. 2

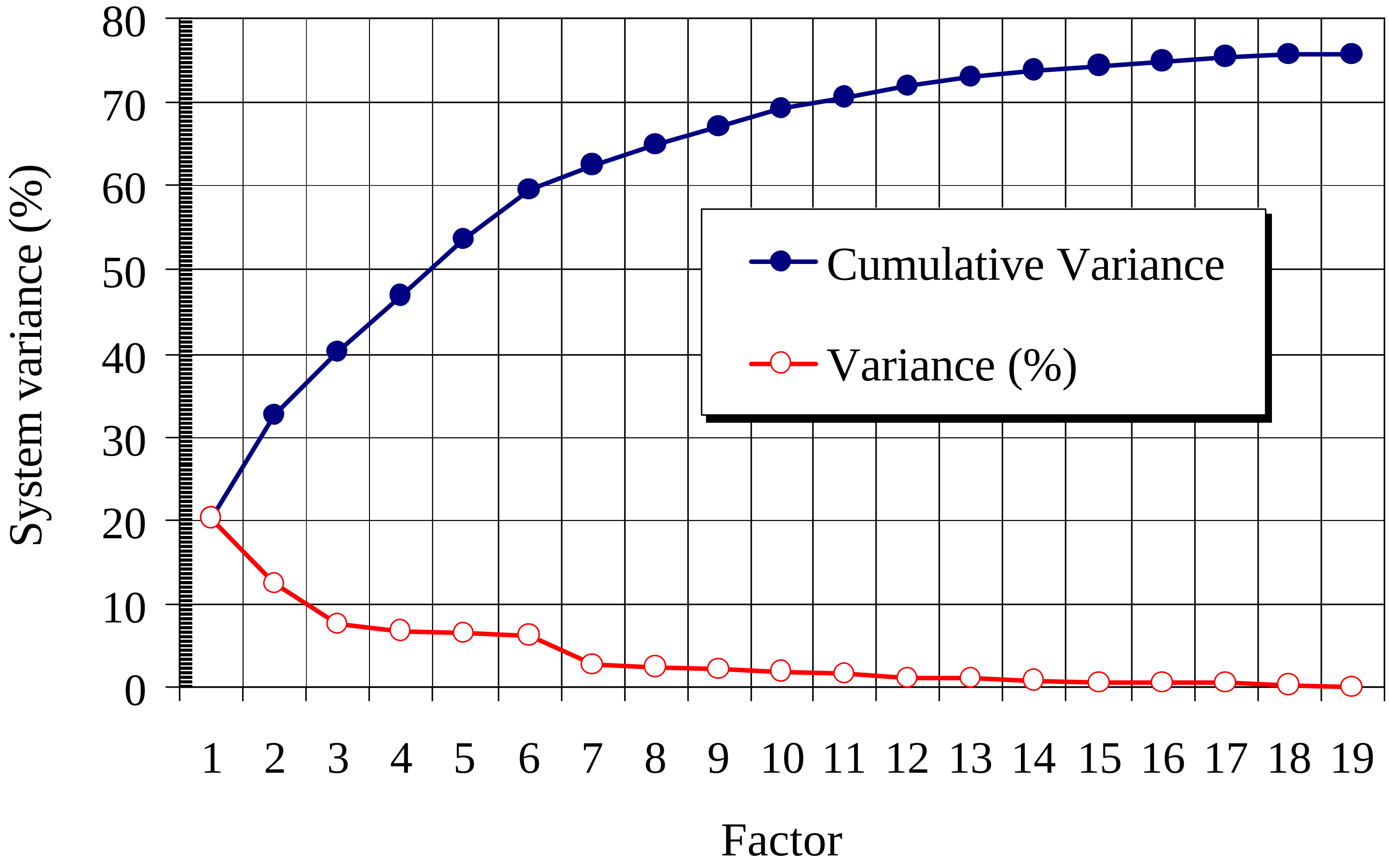

80
70
60
50
40
30
20
10
0
System variance (%)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Factor
Cumulative Variance
Variance (%)

Fig.3

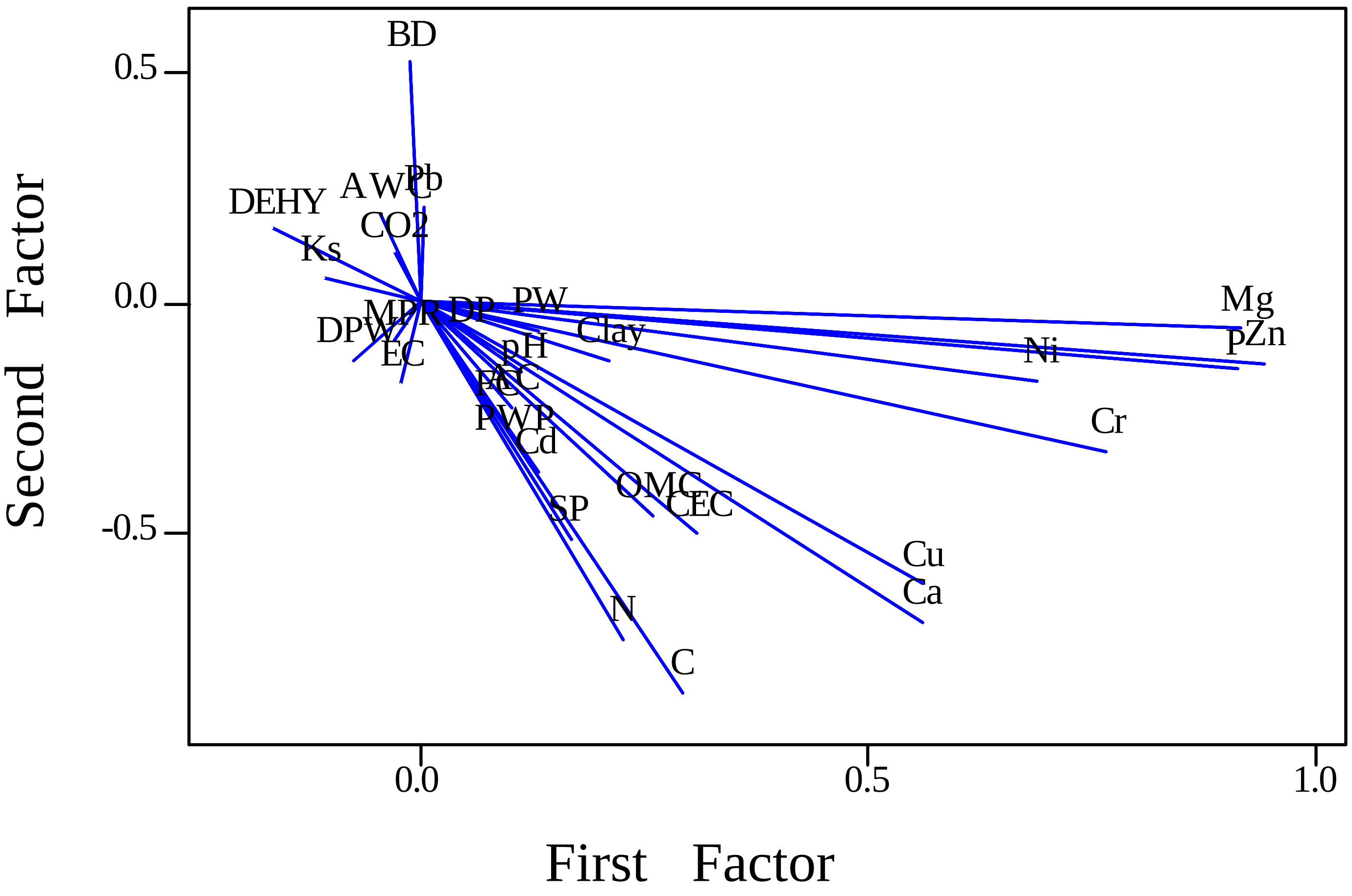

BD
0.5
AWC
Pb
DEHY
CO2
Ks
0.0
MPR
DP
PW
Mg
DPW
Clay
P
Zn
EC
pH
Ni
FC
AC
PWP
Cr
Cd
OMC
CEC
SP
-0.5
Cu
Ca
N
C
0.0
0.5
1.0
Second Factor
First Factor

Fig.4

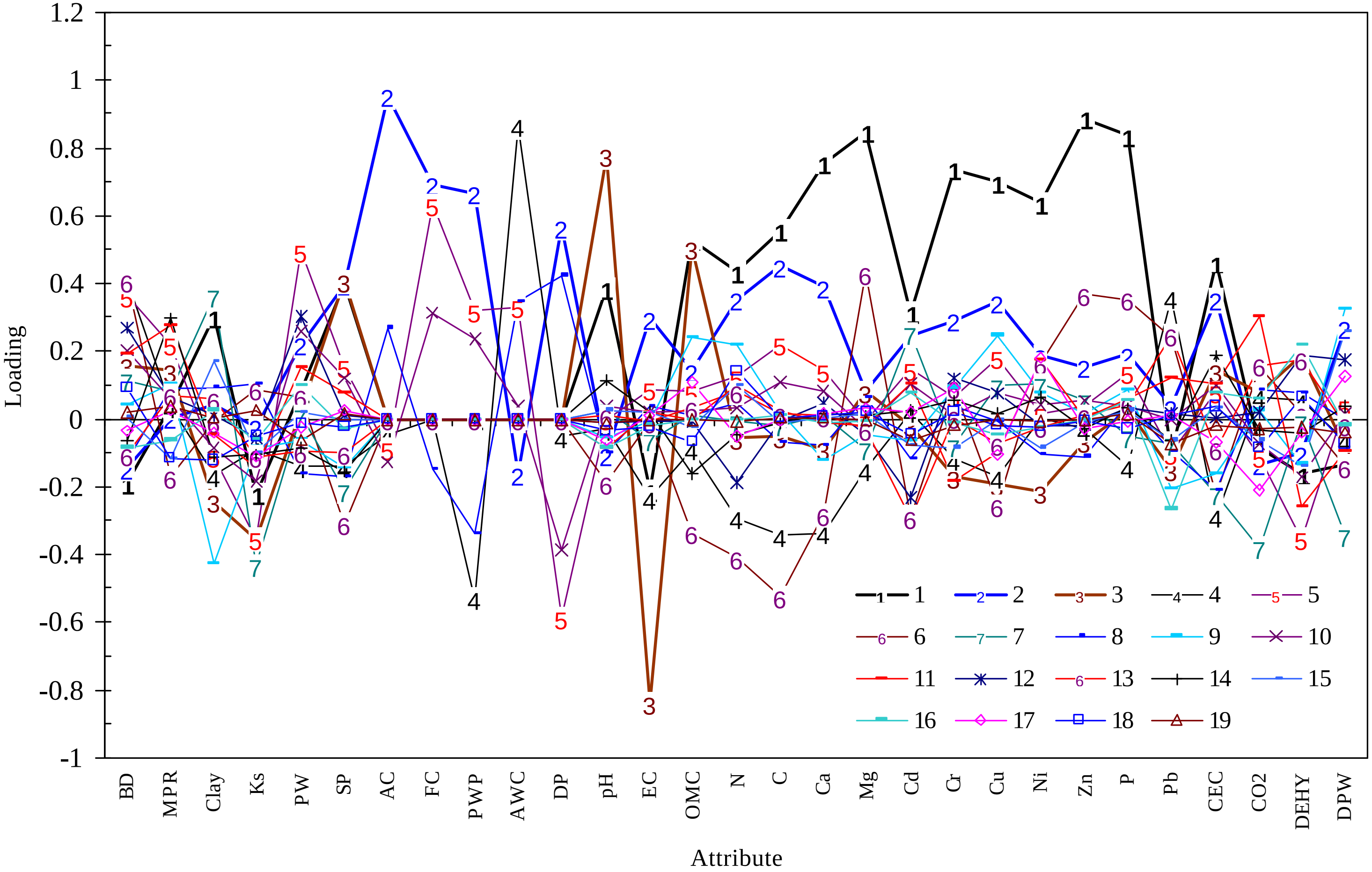
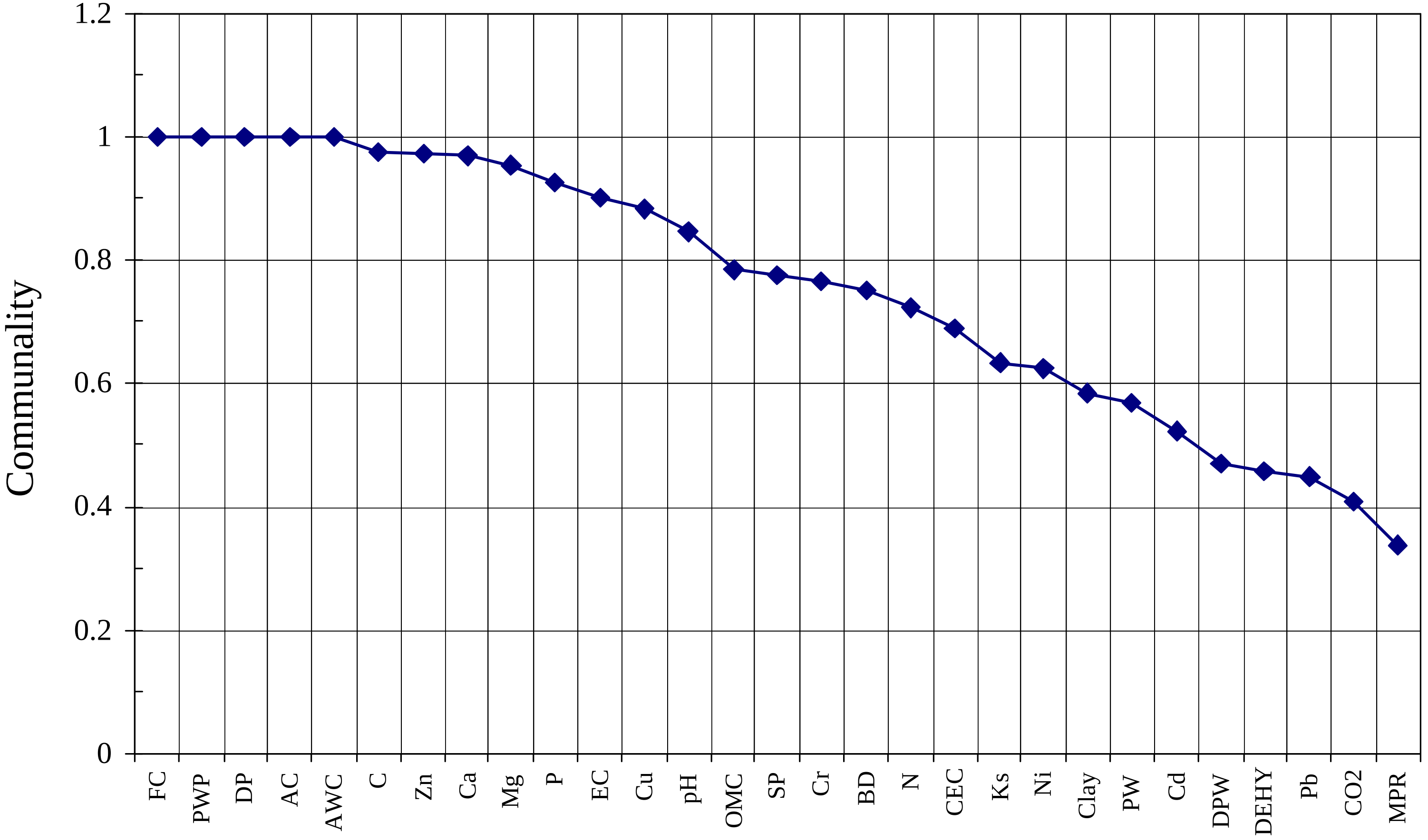

1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Loading
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
C
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CEC
CO2
DEHY
DPW
Attribute
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

Fig.5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0.2
0
FC
PWP
DP
AC
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C
Zn
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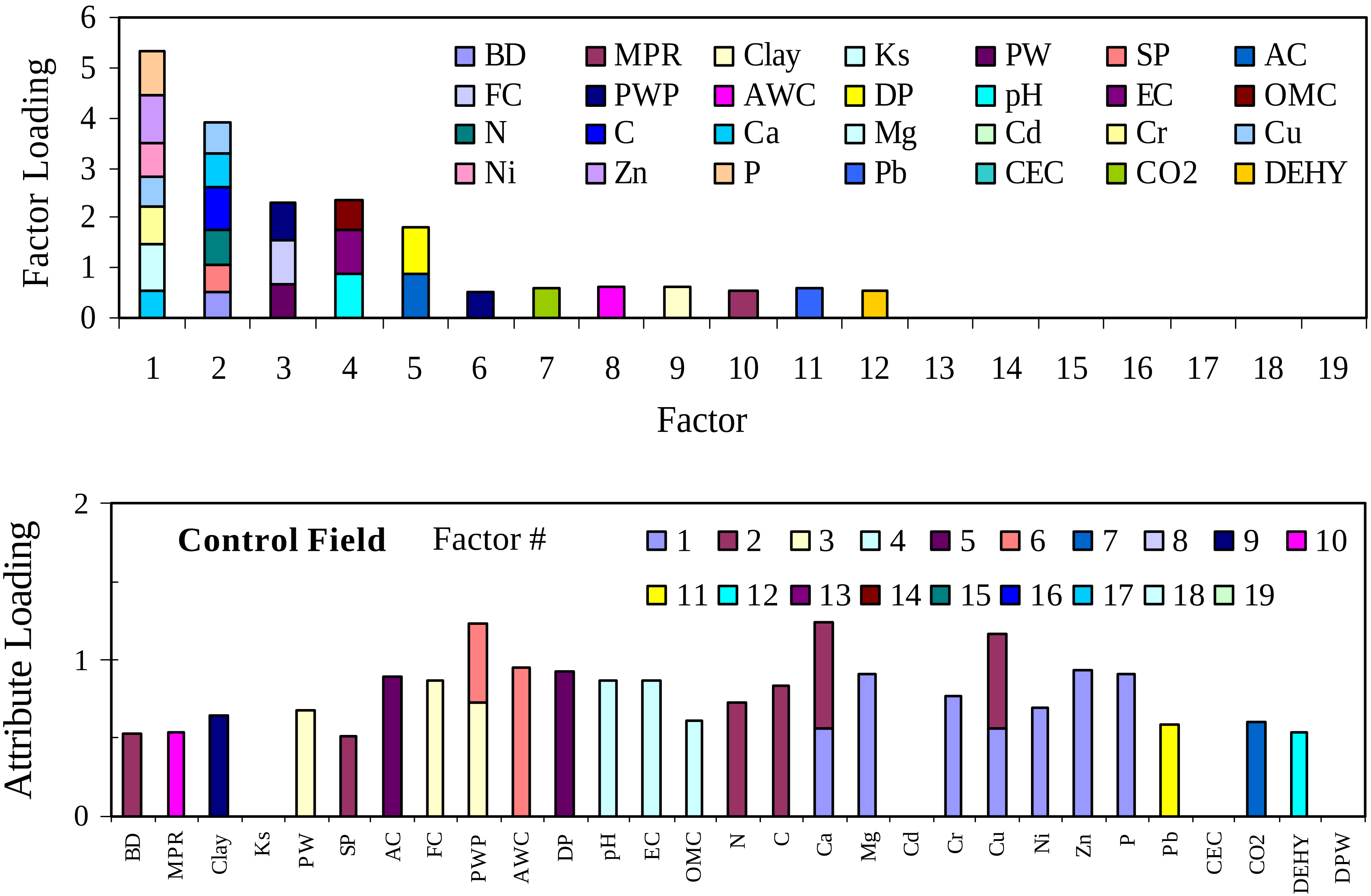
Mg
P
EC
Cu
pH
OMC
SP
Cr
BD
N
CEC
Ks
Ni
Clay
PW
Cd
DPW
DEHY
Pb
CO2
MPR

Fig.6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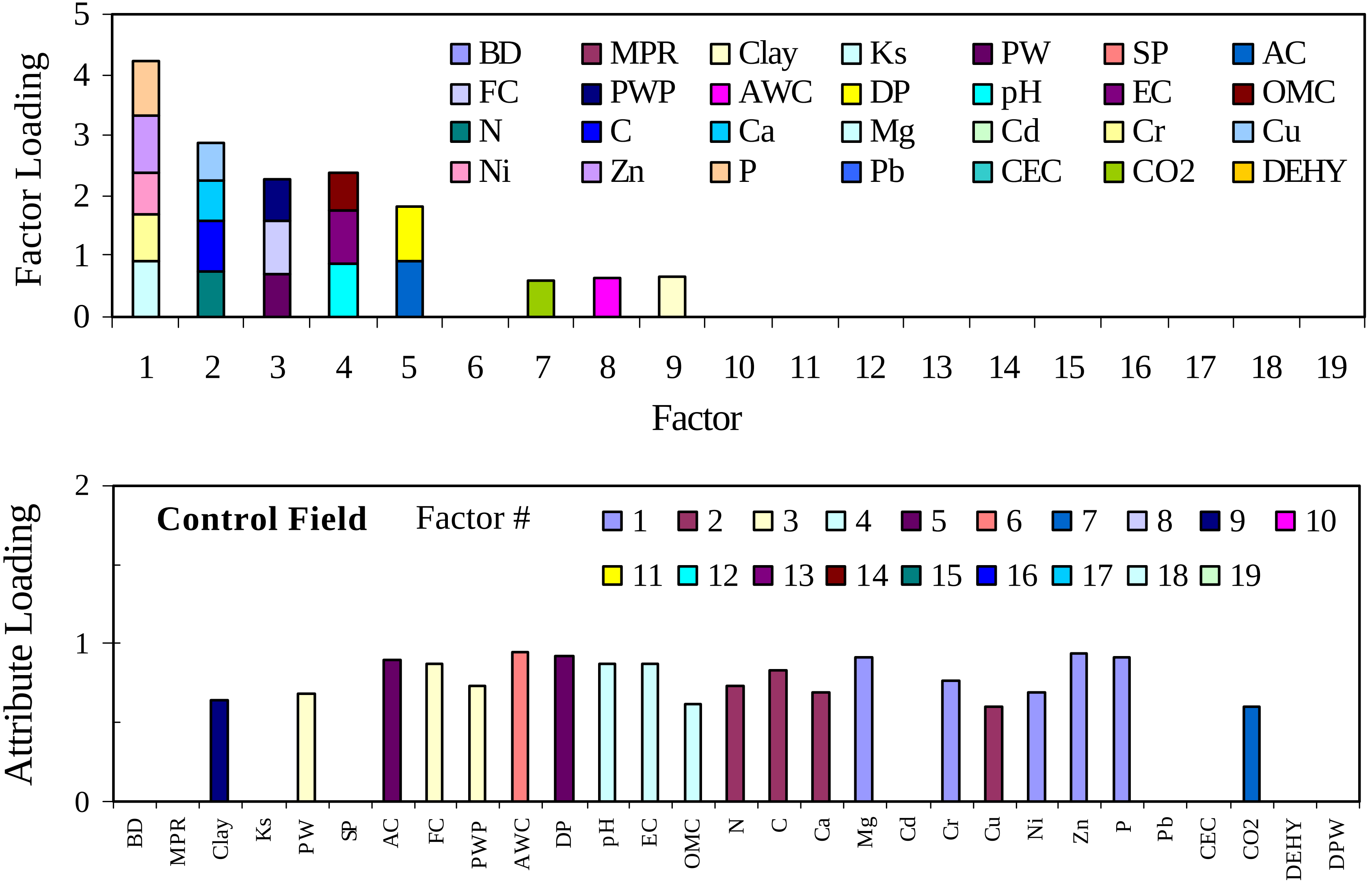
2
3
4
5
6
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
C
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CEC
CO2
DEHY
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Factor
Attribute Loading
0
1
2
Control Field
Factor #
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
C
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CEC
CO2
DEHY
DPW

Fig.7



Factor Loading
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2
3
4
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BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
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OMC
N
C
Ca
Mg
Cd
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P
Pb
CEC
CO2
DEHY
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Factor
Attribute Loading
0
1
2
Control Field
Factor #
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
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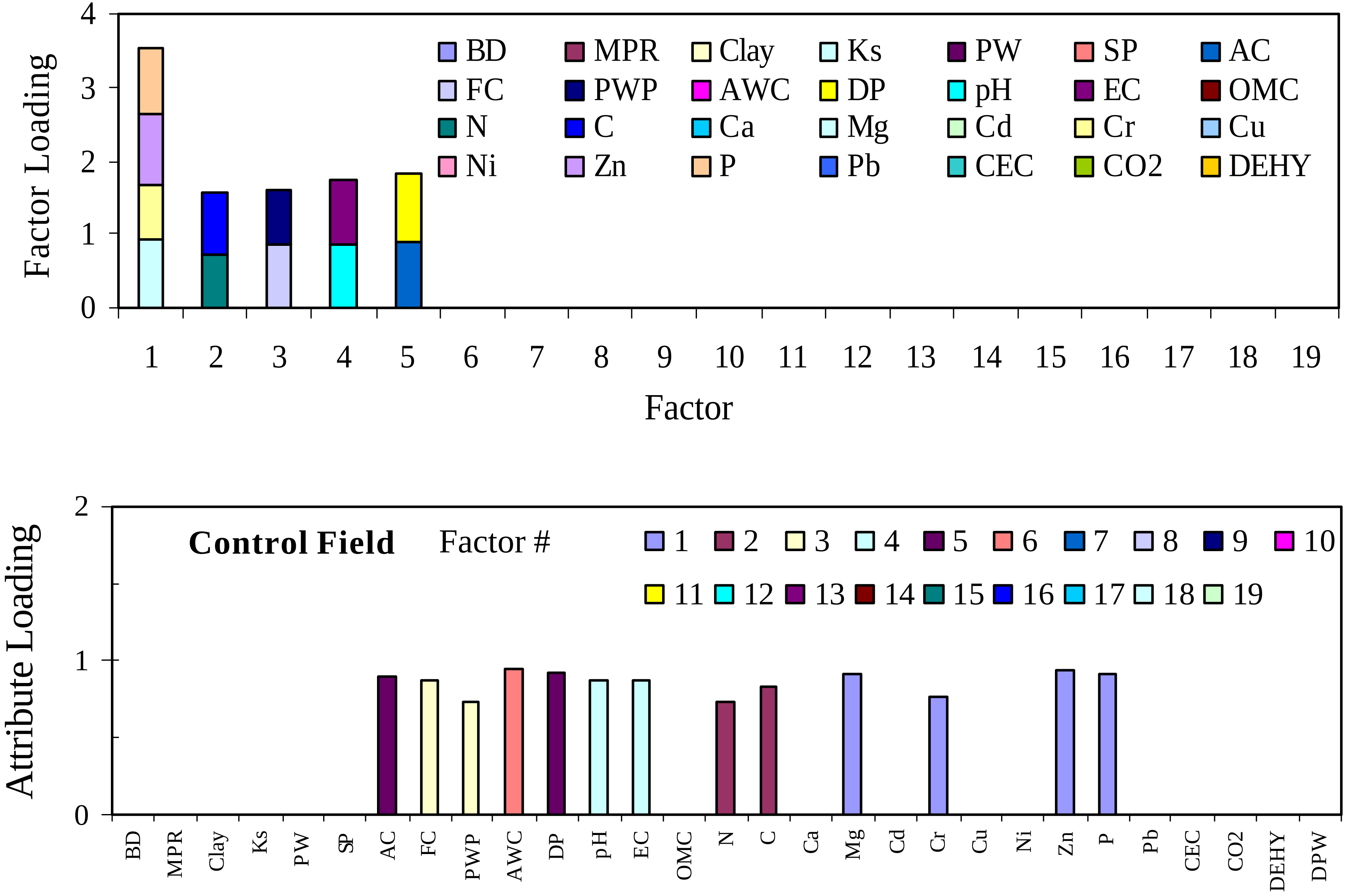
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CEC
CO2
DEHY
DPW

Fig.8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2
3
4
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
C
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CEC
CO2
DEHY
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Factor
Attribute Loading
0
1
2
Control Field
Factor #
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
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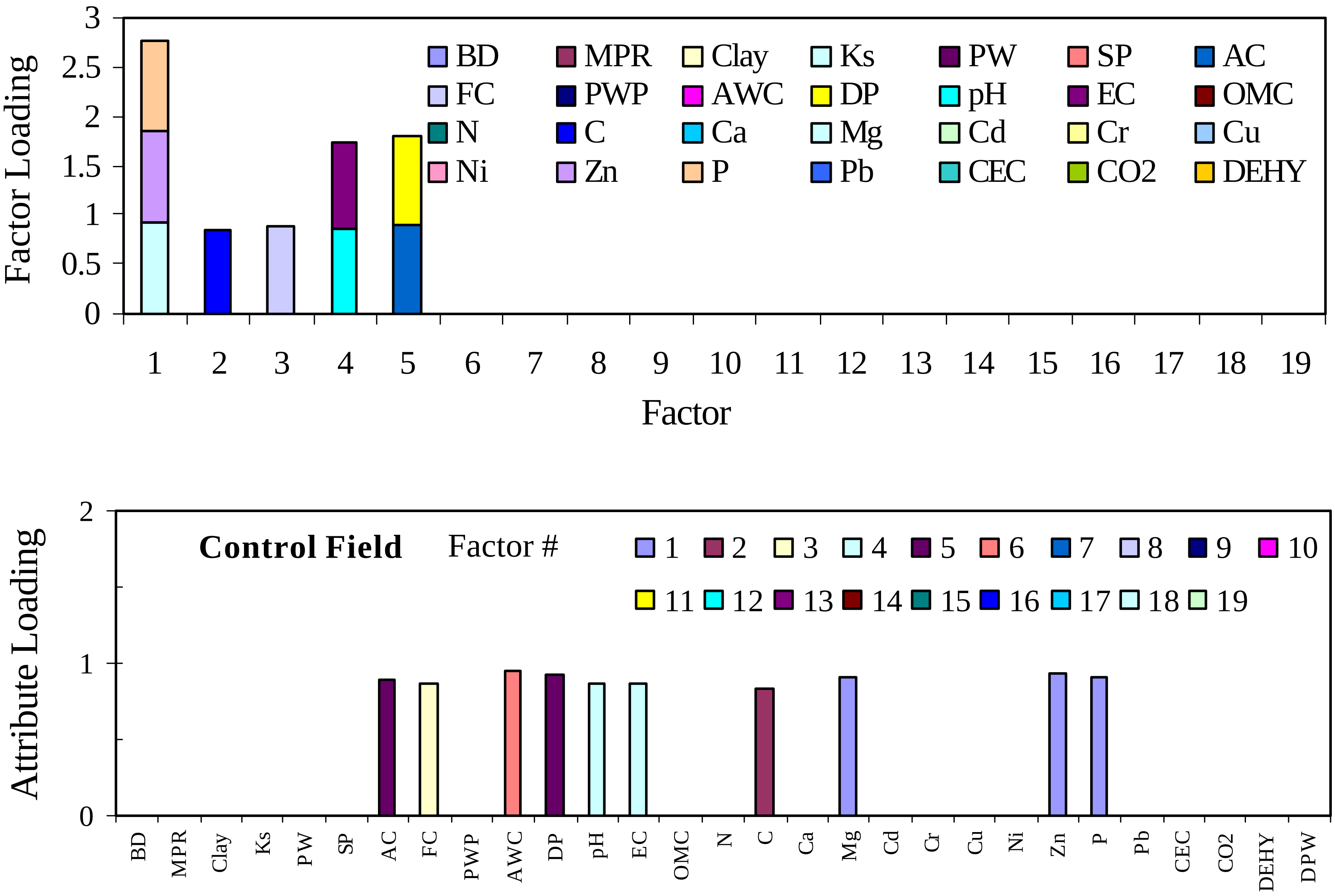
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CEC
CO2
DEHY
DPW

Fig.9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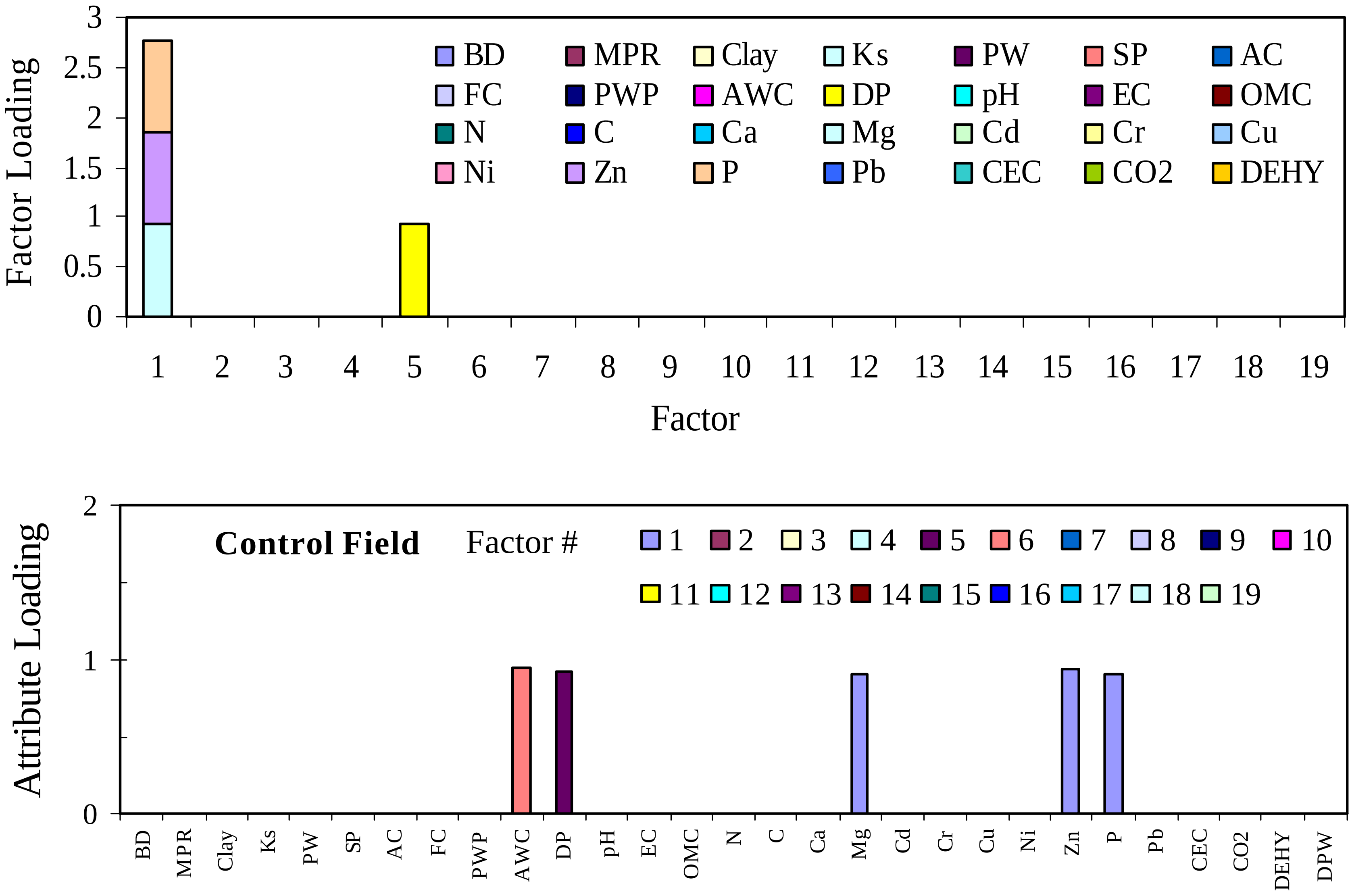
FC PWP AWC DP pH EC OMC
N C Ca Mg Cd Cr Cu
Ni Zn P Pb CEC CO2 DEHY
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Factor
Attribute Loading
2
1
0
Control Field
Factor #
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19
BD MPR Clay Ks PW SP AC FC PWP AWC DP pH EC OMC N C Ca Mg Cd Cr Cu Ni Zn P Pb CEC CO2 DEHY DPW

Fig.10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2
1.5
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0.5
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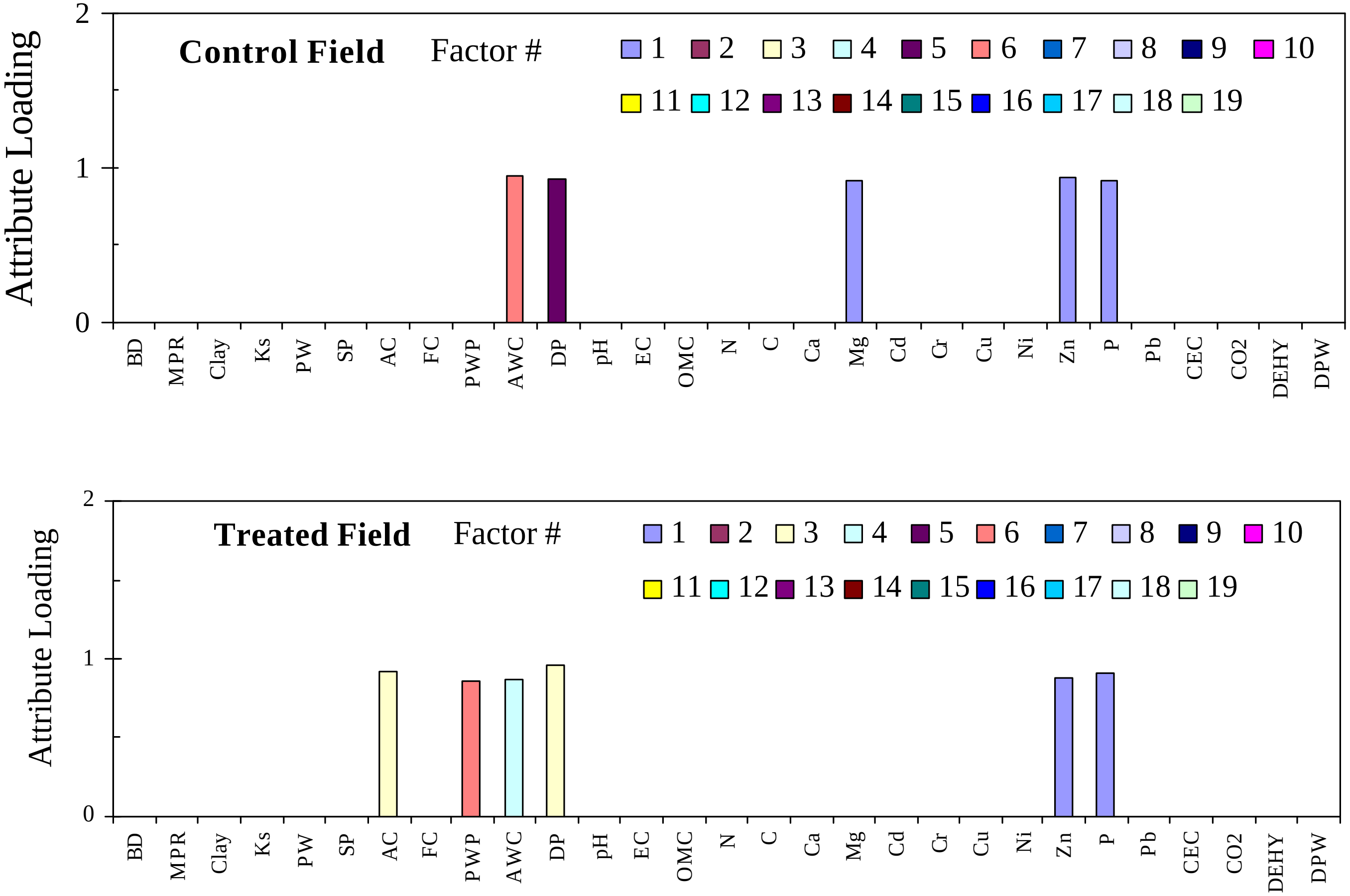
BD
MPR
Clay
Ks
PW
SP
AC
FC
PWP
AWC
DP
pH
EC
OMC
N
C
Ca
Mg
Cd
Cr
Cu
Ni
Zn
P
Pb
CEC
CO2
DEHY
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Factor
Attribute Loading
2
1
0
Control Field
Factor #
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19
BD MPR Clay Ks PW SP AC FC PWP AWC DP pH EC OMC N C Ca Mg Cd Cr Cu Ni Zn P Pb CEC CO2 DEHY DPW

Fig.11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Factor #
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2
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Treated Field
Factor #
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11 12 13 14 15 16 17 18 19
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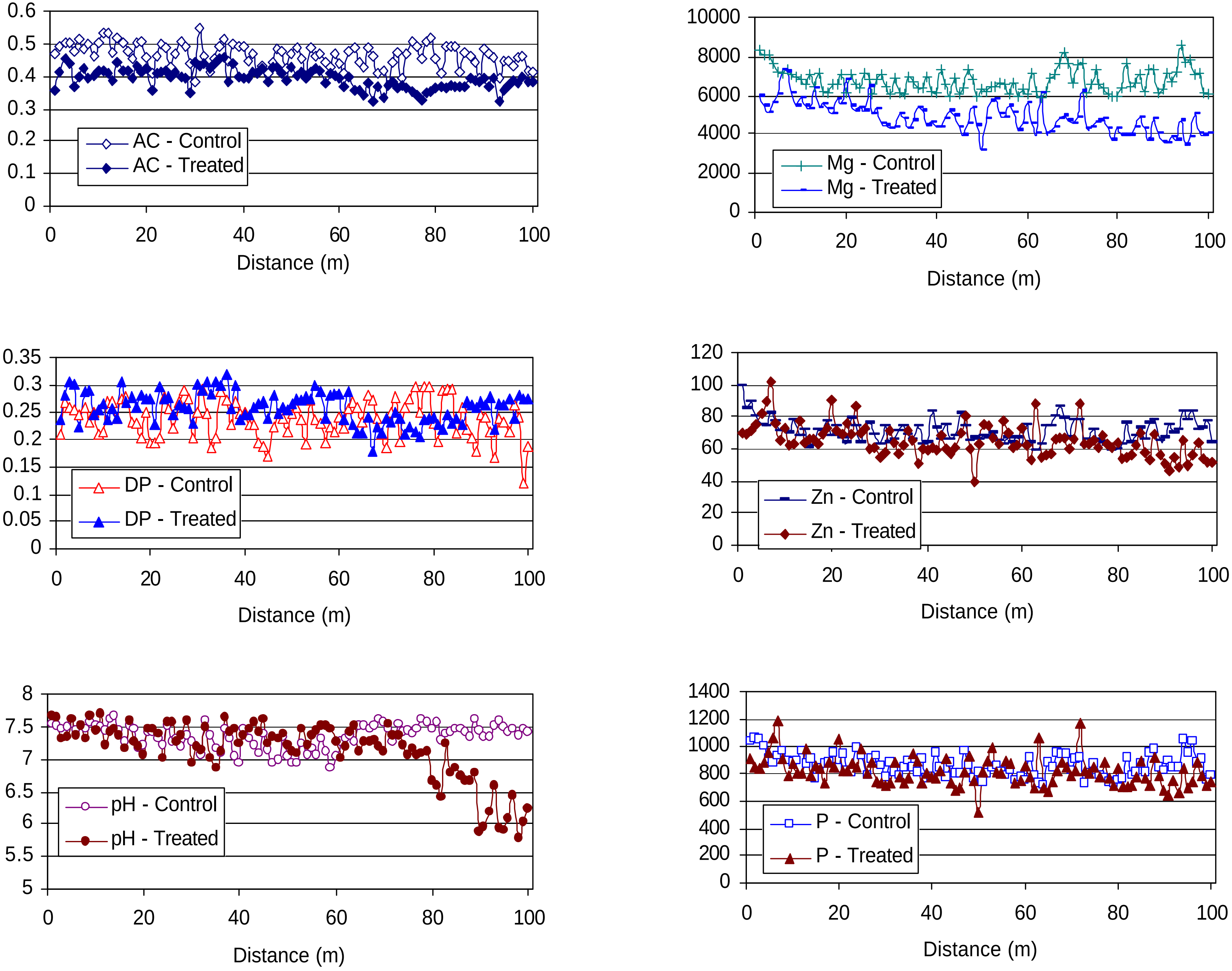
2
BD MPR Clay Ks PW SP AC FC PWP AWC DP pH EC OMC N C Ca Mg Cd Cr Cu Ni Zn P Pb CEC CO2 DEHY DPW

Fig.12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0.3
0.2
0.1
0
0
20
40
60
80
100
Distance (m)
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AC - Treated
10000
8000
6000
4000
2000
0
0
20
40
60
80
100
Distance (m)
Mg - Control
Mg - Treated
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
Distance (m)
DP - Control
DP - Treated
120
100
80
60
40
20
0
0
20
40
60
80
100
Distance (m)
Zn - Control
Zn - Treated
8
7.5
7
6.5
6
5.5
5
0
20
40
60
80
100
Distance (m)
pH - Control
pH - Treated
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Distance (m)
P - Control
P - Treated

Fig.13