CHAPTER 3

EXPLORING THE SPATIAL RELATIONS BETWEEN PLANT ELEMENT UPTAKE OF A LUCERNE STAND AND SOIL PROPERTIES

A.Venter[2*], D.J.Beukes[1], A.S. Claassens[2] & M. Van Meirvenne[3]

[1]ARC-Institute for Soil, Climate and Water, Private Bag X79, 0001, Pretoria, South Africa

[2]Department of Plant Production and Soil Science, University of Pretoria, 0002, Pretoria, South Africa

[3]Dept. Soil Management and Soil Care, Ghent University, Coupure 653, 9000 Ghent, Belgium

3.1 Abstract

There are several factors affecting the nutrient requirements of lucerne (*Medicago sativa* L.) of which yield level, cutting schedule, climate and management practices are the most important. Successful lucerne stands are obtained on deep, well-drained soils with pH(H_2O) = 6.2 - 7.8, P(Bray1) $\geq$ 25 mg kg^{-1}, K $\geq$ 80 mg kg^{-1}, Ca $\geq$ 600 mg kg^{-1} and Mg $\geq$ 600 mg kg^{-1}. This study was designed to quantify the spatial variability of the soil and plant properties and, consequently, to explore the spatial relations between plant element uptake and soil properties using geostatistical procedures. Seventy-two sampling points (nodes) were laid out on a 20 m square grid, with an additional 90 sampling points laid out on a 2.5 m square grid at six randomly selected node points to ensure that the total spatial structure would be identified. Plant and soil samples (0 – 300 mm layer) were collected in June 2001 and analyzed for several plant and soil properties. Linear regression analyses, in general, showed poor correlation between plant element uptake and soil properties. Geostatistical analyses of plant and soil variables produced considerable variation and highly variable autocorrelation lengths. When comparing spatial maps of plant Ca, Mg and P contents with their soil counterparts, no resemblance could be found, while for K some spatial agreement between plant and soil values was noticeable. Making use of a multiple regression equation, very good agreement was found between the spatial distribution of measured and predicted plant K. This emphasizes the fact that the uptake of elements by plants is not solely dependent on the concentrations thereof in the soil solution, but on other factors as well.

3.2 Introduction

There are several factors affecting the nutrient requirements of lucerne (*Medicago sativa* L.) of which yield level, cutting schedule, climate and management are the most important (Lanyon & Griffith, 1988). Studies show that there is a substantial increase in yield in response to nutrient applications and that the uptake of all nutrients increases as yield increases. According to Rhykerd and Overdahl (1972), the production of high-yielding lucerne removes much larger amounts of nutrients from the soil than grain crops such as maize or wheat. Thus to obtain high yield levels, soil fertility status and plant nutrient concentrations must be monitored and adjusted to ensure adequate nutrient availability.

The second factor that influences nutrient uptake of lucerne is the cutting schedule. A close relationship exists between lucerne maturity and nutrient concentration. Lucerne is harvested at vegetative to early reproductive growth stages in high-yielding systems. When lucerne is harvested at a less mature growth stage, such as full bud rather than 10% blossom, the leaf-stem ratio is greater with a consistent increase in the concentrations of P, K, Ca and Mg in the herbage. A third factor that influences the nutrient uptake of lucerne is climate. In South Africa, lucerne is produced under a wide range of conditions. In the warmer regions, lucerne is produced throughout the year, which means that there is a continuous demand for nutrients under a range of environmental conditions. Temperature, light intensity, rainfall patterns and day-length change within and between the harvest intervals of the production year. The variation in environmental conditions will influence nutrient concentrations in forage because of changes in the rate of dry matter production, ion movement in the soil, root activity and the uptake of nutrients by the plant. The fourth factor that influences the nutrient uptake of lucerne is the management practices. Successful lucerne stands are obtained on deep, well-drained soils with pH(H_2O) = 6.2 - 7.8, P(Bray1) $\geq$ 25 mg kg^{-1}, K $\geq$ 80 mg kg^{-1}, Ca $\geq$ 600 mg kg^{-1} and Mg $\geq$ 600 mg kg^{-1} (Fertilizer Society of South Africa, 1991). Traditionally, spatial variation of soil parameters is managed by grouping soils together in seemingly homogeneous units and assuming variability within the units to be purely random or spatially uncorrelated. This approach results in the field being managed by uniform practices such as sowing, fertilizer and pesticide applications and ignoring the spatial variability of the soil and hence the site-specific crop requirements (McBratney & Pringle, 1997).

Today, however, the spatial variation within a field can be managed with the use of geostatistical techniques to ensure cost effective management practices and the optimal use of resources. The aims of this study were to quantify the spatial variability of selected soil and plant properties and, consequently, to explore the spatial relations between plant element uptake and soil properties.

3.3 Materials and Methods

3.3.1 Field and analytical methods

The study was conducted from June 2001 to February 2002 on an 18 ha lucerne stand in the Brits district in the North West Province of South Africa (27°49'E, 25°33'S). The area has a mean annual rainfall of 650 mm and the geology consists of ferrogabro and -diorite with bands and bodies of magnetite. A rectangular area of 160 m X 140 m was demarcated as the study area. The latter consisted of two soil mapping units, which were classified as a deep (1100 mm) Hutton form (Stella family) in the southwesterly corner and a deep (1000mm) Shortlands form (Pyramid family) towards the northeasterly part of the field (Venter,Beukes, Claassens & Van Meirvenne, 2003). The lucerne stand was 2 years old when the trial commenced, and had been irrigated by a sprinkler irrigation system. At the establishment of the stand, 500 kg ha^{-1} superphosphate and 200 kg ha^{-1} potassium chloride were applied as fertilizer. Seventy two-sampling points (nodes) were laid out on a 20 m square grid, with an additional 90 points on a 2.5 m square grid at six randomly selected node points to ensure that the total spatial structure would be identified. Figure 3.1 shows an aerial photograph of the field with the sampling points depicted as small black dots.

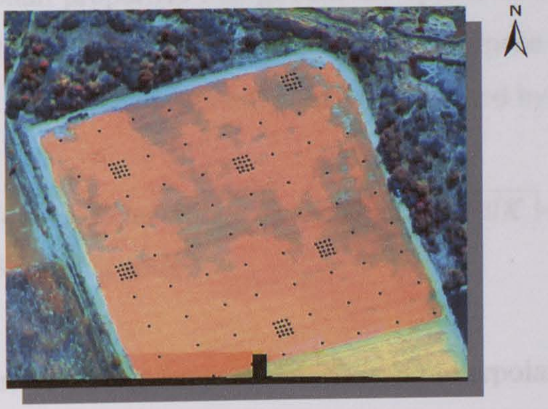

Figure 3.1 An aerial photograph of the field. The black dots depict the sampling points.

Starting in June 2001, yield sampling was done on six occasions, at approximate intervals of 5 weeks. The plant samples of the June 2001 harvest were analyzed for potassium (K), calcium (Ca), magnesium (Mg) and phosphate (P) content using standard methods (Agri Laboratory Association of Southern Africa, 1998). Soil samples taken at the sampling points were analyzed for K, Ca, Mg, sodium (Na), P and organic C content, as well as for pH(H_2O), electrical resistance, texture and water retention (at -33kPa) using standard methods (Non-Affiliated Soil Analysis Work Committee, 1990). Details of the experimental layout, sampling and analytical procedures are reported elsewhere (Venter *et al*., 2003). Soil and plant analysis results are given in Table 3.1. The plants were cut at an early flowering stage and analyses were performed on the whole plant.

3.3.2 Statistical methods

Basic statistical analyses (Hintze, 1997) were performed to obtain information on the frequency distribution, standard deviation and coefficients of variation on all soil and plant properties (Venter *et al*., 2003). These preliminary analyses indicated that most of the soil properties had a positively skewed distribution, and several transformations (logarithmic, $\log_e$ and square-root) were performed prior to subsequent analyses. All plant properties displayed a normal distribution and no transformations were conducted. Table 3.2 shows the linear correlations of some of the soil and plant properties.

An all-possible regression (step-wise regression) was performed, using the point data, to identify the primary soil and plant properties that govern the uptake of each plant nutrient, and was used to generate a dataset for geostatistical analyses. For the purpose of this paper only the model for the prediction of plant K will be discussed, which is described by:

$$\begin{aligned} PedictedPlantK &= 1.745 - 5.339e^{-5}(SoilCa) + 9.659e^{-2}\left(\sqrt{SoilK}\right) + 1.829e^{-3}(Silt) + \\ &3.367e^{-1}(PlantCa) - 3.693(PlantMg) \end{aligned} \tag{3.1}$$

($R^2 = 0.58$)

Geostatistical analyses, including the use of the kriging interpolation technique to generate spatial presentations of the variation in the soil and plant properties, were performed (Hunt, 2002). The spatial structure of these properties is described by the semi-variance, which is estimated as the average of the squared differences between all observations separated by a lag distance. Consequently the points that are closer together will have smaller semi-variances than the points that are further apart. A semi-variogram is generated by plotting the semi-variance against the lag and is modelled by a mathematical function. Kriging interpolation is then used to estimate values at unsampled locations, which can be mapped (Webster & Oliver, 2000). In those cases where data populations were normally distributed, standard semi-variograms and ordinary kriging were used for estimation purposes. For bi-modal data populations the indicator kriging method was used (Goovaerts, 1997; Hunt, 2002). All estimates were contoured and mapped (Golden Software Inc., 1995) to illustrate the spatial variability of properties.

For the purpose of this paper the spatial variability of only four elements (Ca, Mg, K and P) for both plant and soil will be discussed. Of all the elements, only the Mg content of the soil exhibited a bi-modal distribution, reflecting the presence of two soil types within the experimental area. This necessitated the use of indicator kriging (IK) to estimate this property. According to Webster and Oliver (2000), indicator kriging is a non-linear, non-parametric form of kriging in which continuous variables are converted to binary ones (indicators). This makes this approach suited to non-normal and crude data. The dataset was divided into nine percentile ranges (Isaaks & Srivastava, 1989) that served as the threshold values. An isotropic, indicator semi-variogram was computed for each of the percentile ranges and was then used to do an indicator kriging analysis. All other properties were estimated using ordinary kriging (OK). The variograms of these properties are shown in Figures 3.2 and 3.4 and the model parameters are given in Table 3.3. The maps of the kriged estimates for the measured plant and soil properties are shown in Figure 3.3, and that of predicted plant K in Figure 3.4.

3.4 Results and Discussion

3.4.1 Plant and Soil characteristics

The two experimental soils have apedal (Stella) and blocky structure (Pyramid) B-horizons. Dominant clay minerals in the A horizon are kaolinite and smectite, respectively. Both soils are deep (1000 – 1100 mm) and have high clay contents (43 – 54 % clay). Soil chemical properties like pH(H_2O), Ca and Mg are markedly different between the two soils (Venter *et al*., 2003). The observed soil pH(H_2O) (too high) and P (too low) (FSSA, 1991) are not conducive to optimal lucerne growth. However, according to the norms of Reuter and Robinson (1997), there were adequate concentrations of all nutrients in the plants (Table 3.1).

Table 3.1 Statistical descriptions of some soil and plant properties.

		Minimum	**Maximum**	**Mean**	**Median**	**Std. dev.**	**CV**
Soil	**pH(H_2O)**	7.5	9.0	8.3	8.4	0.4	0.05
	Org. C (%)	0.88	1.48	1.15	1.14	0.14	0.12
	Ca (mg kg^{-1})	1565	8657	4798	5140	1570	0.33
	Mg (mg kg^{-1})	399	1917	1116	945	451	0.40
	K (mg kg^{-1})	94	468	222	221	65	0.30
	P (mg kg^{-1})	5.10	65.19	19.35	16.55	9.91	0.51
	Clay (%)	38	50	43	42	3	0.06
	Sand (%)	21.1	47.2	34.7	34.9	5.4	0.16
	Water retention (% at -33kPa)	16.4	37.5	27.3	26.9	3.9	0.14
Plant	**Ca (%)**	0.92	1.80	1.35	1.34	0.18	0.13
	Mg (%)	0.20	0.47	0.32	0.32	0.05	0.17
	K (%)	1.30	3.49	2.22	2.28	0.39	0.18
	P (%)	0.18	0.40	0.31	0.31	0.04	0.13
	Yield (t ha^{-1})	1.6	10.7	5.7	5.4	2.0	0.36

Table 3.2 shows that the correlations between soil and plant Mg, and K are relatively high (r = 0.49 and r = 0.45, respectively) while the correlations between the Ca and P content of the plants and soil are poor (r = -0.13 and r = 0.10, respectively). The better correlations between the plant and soil Mg and K may be due to the high uptake rate of both elements through the plant membrane and a high mobility throughout the entire plant. In the soil, K and Mg ions are adsorbed by clay minerals, and thus the behaviour of K and Mg in the soil is very much dependent on the clay content and types of clay minerals present (Mengel & Kirkby, 1987). The two soil types are dominated by kaolinite and smectite clay minerals, neither of which seems to have affected the adsorption of K. Although Mg also has a high rate of uptake, it is much lower

than that of K but it is also mobile in the phloem, which means that it can be translocated from older to younger leaves or to the apex.

Table 3.2 A correlation matrix of some of the soil and plant properties.

		Plant				*Soil*								
		Ca	**Mg**	**K**	**P**	**Ca**	**Mg**	**K**	**P**	**pH**	**C**	**WR**	**Clay**	**Sand**
Plant	**Ca**	1												
	Mg	0.05	1											
	K	0.09	-0.61	1										
	P	0.38	-0.01	0.07	1									
Soil	**Ca**	-0.13	0.34	-0.09	-0.20	1								
	Mg	-0.30	0.49	-0.23	-0.20	0.83	1							
	K	-0.15	-0.08	0.45	-0.12	0.57	0.39	1						
	P	-0.08	-0.32	0.22	0.08	-0.57	-0.50	-0.01	1					
	pH	-0.24	0.33	-0.06	-0.36	0.77	0.78	0.37	-0.52	1				
	C	0.35	-0.32	0.26	0.29	-0.28	-0.54	0.20	0.30	-0.62	1			
	WR	0.14	0.18	0.05	0.03	0.72	0.57	0.51	-0.48	0.53	0.04	1		
	Clay	0.03	0.08	0.00	0.06	0.36	0.30	0.20	-0.39	0.18	0.10	0.55	1	
	Sand	-0.27	-0.09	-0.10	-0.03	-0.53	-0.30	-0.36	0.52	-0.33	-0.22	-0.77	-0.70	1

pH = pH(H_2O)

WR = water retention at –33kPa

In contrast to the foregoing uptake phenomena, the uptake rate of Ca by plants is lower and is therefore little affected by the Ca content in the root medium, provided that the Ca availability is adequate for normal plant growth (Mengel & Kirkby, 1987). The weak correlation that exists between the soil Ca content and that of the plants can be explained by the fact that part of the high Ca content of soils is precipitated and therefore not active. Phosphorus moves through the soil solution to plant roots by diffusion, which means that it is limited and can only move short distances and may thus be positionally unavailable to the plant roots. In addition to its positional unavailability, lucerne roots absorb P largely as orthophosphate ($H_2PO_4^-$) from the soil solution (Lanyon & Griffith, 1988), which is influenced by pH. In alkaline soils, where Ca phosphates dominate, soluble P is decreased by an increase in pH and may be less available to plants.

3.4.2 Spatial analyses

All of the variograms reached an upper boundary, *i.e.* a sill at a certain lag distance or range (Figure 3.2). Data locations separated by a distance beyond the range are regarded as spatially independent (Webster & Oliver, 2000).

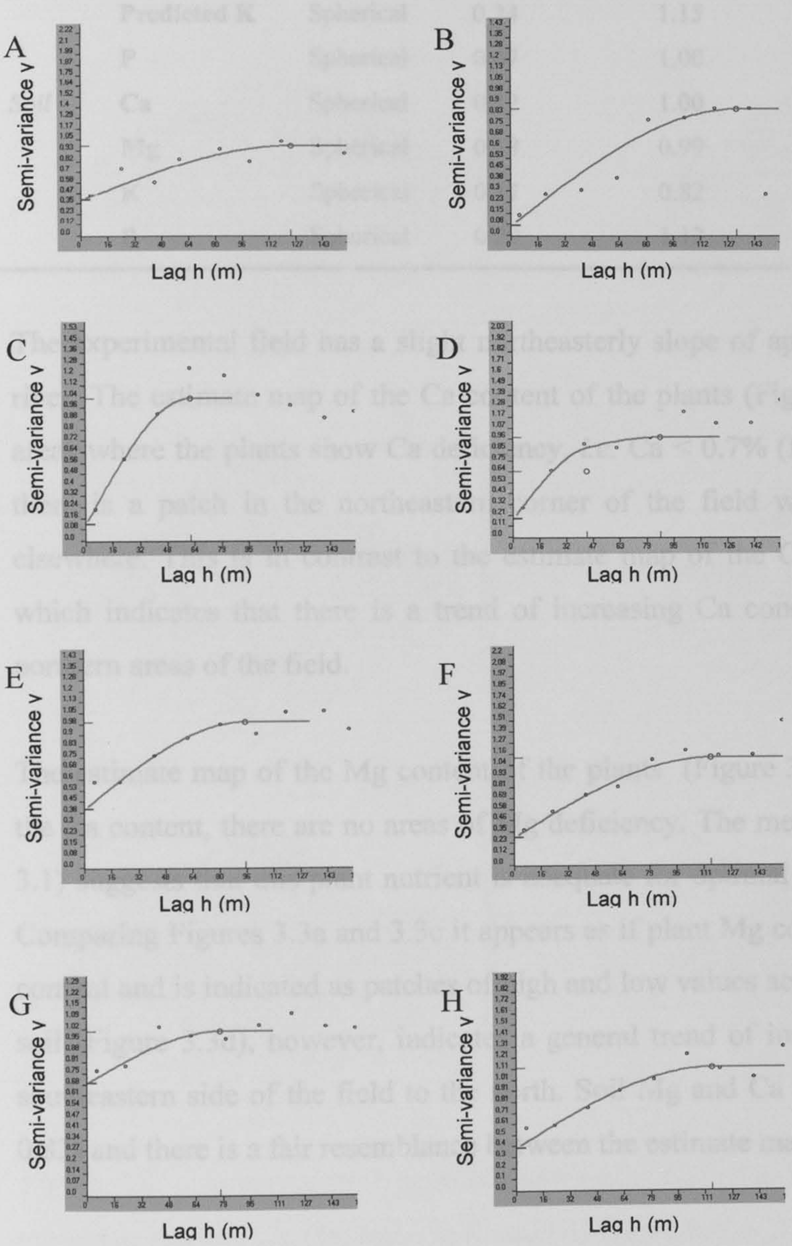

Figure 3.2 Experimental variograms with the fitted model for (A) Ca, (C) Mg, (E) K and (G) P contents of the plants and (B) Ca, (D) Mg, (F) K and (H) P contents of the soil.

Table 3.3 Model parameters for plant and soil analysis

		Model	**Nugget (c_0)**	**Sill ($c+c_0$)**	**Long range (a) (m)**	**Short range (a) (m)**
Plant	**Ca**	Spherical	0.40	1.00	125	55
	Mg	Spherical	0.13	1.04	61	-
	K	Spherical	0.41	1.00	95	59
	Predicted K	Spherical	0.24	1.15	107	56
	P	Spherical	0.67	1.00	73	-
Soil	**Ca**	Spherical	0.12	1.00	175	116
	Mg	Spherical	0.18	0.99	104	-
	K	Spherical	0.17	0.82	75	-
	P	Spherical	0.29	1.13	115	-

The experimental field has a slight northeasterly slope of approximately 2 %, ending in a small river. The estimate map of the Ca content of the plants (Figure 3.3a) indicates that there are no areas where the plants show Ca deficiency, *i.e.* Ca < 0.7% (Reuter & Robinson, 1997), although there is a patch in the northeastern corner of the field where the Ca content is lower than elsewhere. This is in contrast to the estimate map of the Ca content of the soil (Figure 3.3b), which indicates that there is a trend of increasing Ca concentration from the southern to the northern areas of the field.

The estimate map of the Mg content of the plants (Figure 3.3c) indicates that, as in the case of the Ca content, there are no areas of Mg deficiency. The mean plant Mg value of 0.32 % (Table 3.1) suggests that this plant nutrient is adequate for optimal growth (Reuter & Robinson, 1997). Comparing Figures 3.3a and 3.3c it appears as if plant Mg content is more variable than plant Ca content and is indicated as patches of high and low values across the field. The Mg content of the soil (Figure 3.3d), however, indicates a general trend of increasing Mg concentration from the southeastern side of the field to the north. Soil Mg and Ca are highly correlated (Table 3.2; r = 0.83) and there is a fair resemblance between the estimate maps of these two variables.

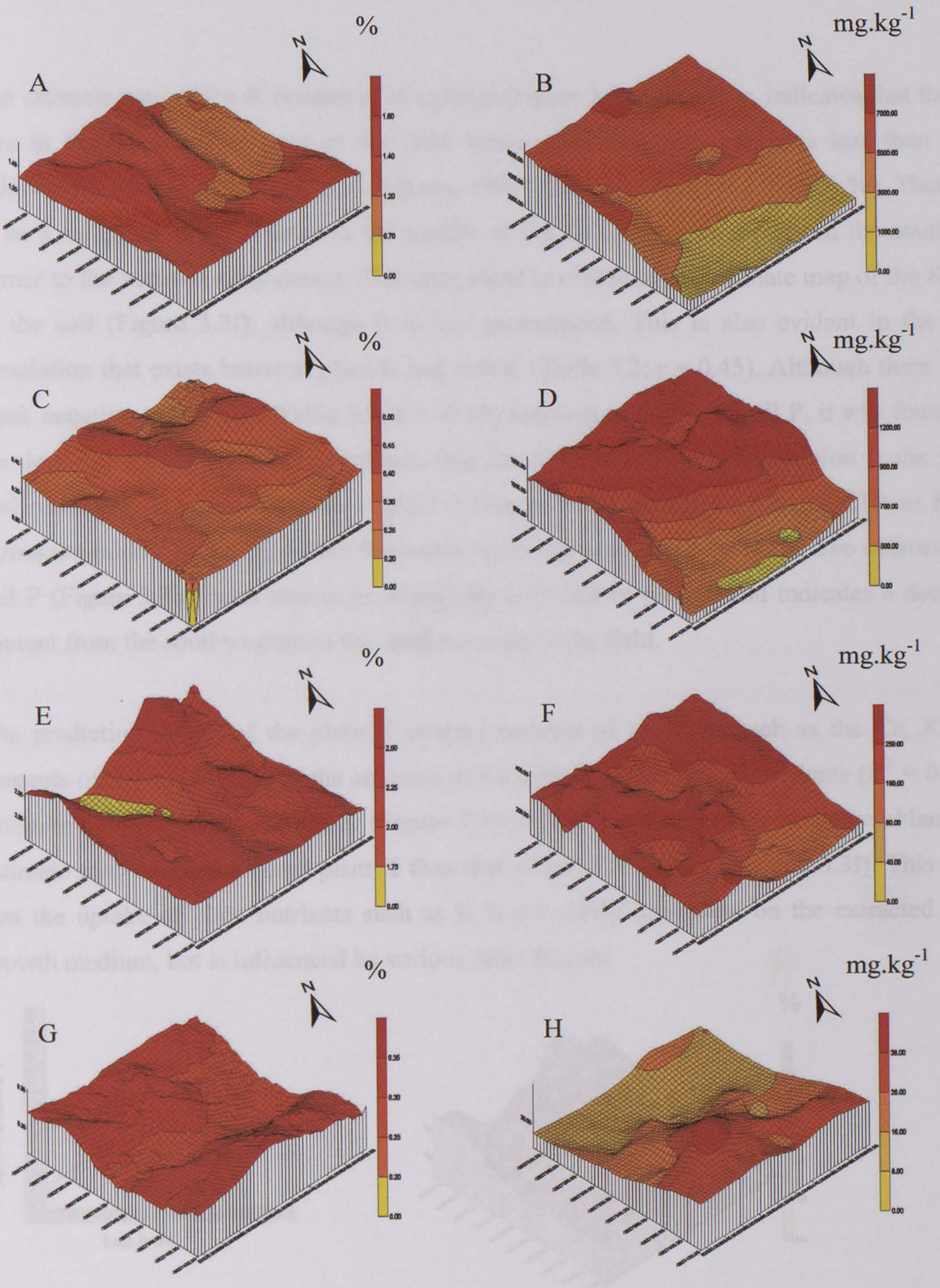

Figure 3.3 Maps of the kriged estimates of the (A) Ca, (C) Mg, (E) K and (G) P contents of the plants and (B) Ca, (D) Mg, (F) K and (H) P contents of the soil.

The estimate map of the K content of the plants (Figure 3.3e), however, indicates that there is an area in the northwesterly part of the field where plant K concentration is less than 1.75 %, indicating a deficiency (Reuter & Robinson, 1997: Adequate range = 2.0 – 3.5 %). There seems to be a trough of low K values in the middle of the field that decreases from the southeasterly corner to the northwesterly corner. The same trend is visible in the estimate map of the K content of the soil (Figure 3.3f), although it is less pronounced. This is also evident in the positive correlation that exists between plant K and soil K (Table 3.2; r = 0.45). Although there is a very weak negative correlation (Table 3.2; r = -0.10) between plant P and soil P, it was found during the development of the semi-variograms that the direction of greatest variation is the same for both variables. The estimate map of plant P (Figure 3.3g) indicates a trough of lower P content across the middle of the field from the northeastern to the southwestern side. The estimate map of soil P (Figure 3.3h) bears almost no resemblance to that of plant P and indicates a decline in P content from the southwestern to the northern parts of the field.

The prediction model of the plant K content consists of variables such as the Ca, K and silt contents of the soil as well as the amounts of Ca and Mg taken up by the plants ($R^2 = 0.58$). The estimate map of predicted plant K (Figure 3.4) yielded a much better visual resemblance to the estimate map of the measured plant K than that of soil K (Figures 3.3e and 3.3f). This indicates that the uptake of plant nutrients such as K is not solely dependent on the extracted K in the growth medium, but is influenced by various other factors.

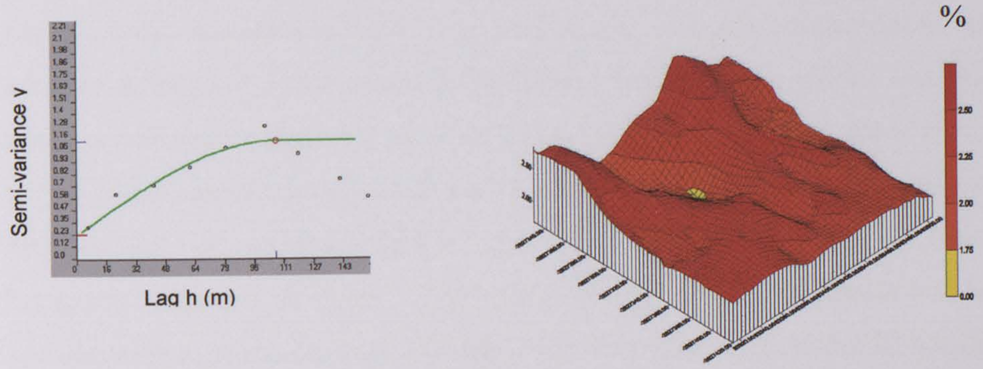

Figure 3.4 Experimental semi-variogram and estimate map of the predicted K in the plants.

3.5 Conclusions

Statistical analyses indicated that the two soil types affected soil and plant properties to different degrees. For some properties (*e.g.* pH, Mg content of the soil and electrical resistance) a distinct bi-modal population resulted, while there was hardly any effect on other properties (all plant element concentrations and organic C, P and K contents of the soil). A linear regression analysis, in general, showed poor correlations between the plant element uptake and soil properties, but with the use of a multiple regression analysis the major plant and soil properties that influenced the uptake of elements by plants were established. Geostatistical procedures allowed the estimation of elements to construct maps in order to demonstrate the spatial variability of plant and soil properties. The majority of variables showed considerable variation and highly variable autocorrelation lengths. This study has shown that there is little or no resemblance when comparing the spatial distribution of lucerne plant Ca, Mg, K and P contents with those of the soil. However, making use of a multiple regression equation, good agreement was found between the spatial distribution of measured and predicted plant K. This emphasizes the fact that the uptake of elements by plants is not solely dependent on the concentrations thereof in the soil solution, but on other factors as well.