CHAPTER 4

SPATIAL RELATIONS OF PLANT ELEMENT UPTAKE AND YIELD OF A LUCERNE STAND OVER TIME

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4.1 Abstract

In general, agricultural fields are managed as uniform units, ignoring spatial and temporal relations between plant element uptake and yield. This study was conducted from June 2001 to February 2002 on a two-year-old lucerne stand and explores the spatial relationships between nutrient uptake and green biomass yield during both winter and summer growing seasons, as well as the temporal variation of lucerne yield during a growing season using geostatistical procedures. Green biomass yield was determined on six occasions at 162 sampling points across the field, while soil and plant sampling and analyses were conducted once in June 2001. Although the lucerne stand contains on average adequate concentrations of Ca, Mg, P and K, areas of K deficiency did occur in the field during both the winter and summer seasons. Weak linear correlations exist between plant elements and yield. Similarities were discernable between winter and summer spatial variations of plant Ca, Mg, P and K. Significant correlations existed between soil and plant Mg and K, and in the case of Mg, exhibited clear spatial similarities. Temporal variations in lucerne yield were observed, with the lowest and highest yields in June and September, respectively. Although there were large differences in spatial variation of lucerne yields across the harvesting events, similar spatial patterns were evident. A clear resemblance between spatial plant K and yield existed, probably because the deficiency in plant K was a dominant factor in causing spatial variation in yield. Although this study revealed spatial and temporal patterns in plant element uptake and yield of a lucerne stand at a specific location, the

results illustrate some useful practical aspects relevant to site-specific management of lucerne stands.

4.2 Introduction

Spatial and temporal variation of soil properties causes uncertainty in agricultural decision-making, but this variation is manageable if it is significant, controllable and predictable (Cook & Bramley, 2000). Traditionally, spatial variation is managed by grouping properties together in seemingly homogeneous units and assuming variability within the units to be purely random or uncorrelated. This results in the field being managed uniformly for activities such as sowing, and fertilizer and pesticide application, ignoring the soil spatial variability and hence the site-specific crop requirement (McBratney & Pringle, 1997). Site-specific management, unfortunately, requires a large investment in collecting the data required to make informed decisions at this scale, and prohibits the adoption of such an intensive management programme. Today, however, the spatial variation within a field can be managed with the use of geostatistical techniques. Based on the premise that the spatial variability of crop yield is influenced by spatial variability in soil factors at a similar scale, researchers have begun to examine the patterns observed in crop yield maps to identify potential management zones within a field as well as to improve sampling scheme designs (Stafford, Ambler, Lark & Catt, 1996; Venter, Beukes, Claassens & Van Meirvenne, 2003a; Frogbrook, Oliver, Salahi & Ellis, 2002). According to Boydell and McBratney (2002), stable yield zone patterns can be identified by using multi-seasonal yield maps.

In South Africa, lucerne (*Medicago sativa* L.) is grown under a wide range of climatic conditions, under dryland and irrigation. According to Fick, Holt and Lugg (1988), the lucerne crop usually shows a corresponding response to a constantly changing environment, which depends on factors such as the age, growth stage, prior condition and genotype of the crop. The objectives of this study were (1) to explore the spatial relationships between nutrient uptake and green biomass yield during both winter and summer growing seasons, and (2) to investigate the temporal variation of lucerne yield during a growing season to identify yield zone patterns in the field.

4.3 Materials and Methods

4.3.1 Field and analytical methods

The study was conducted on an 18 ha lucerne stand in the Brits district in the North West Province of South Africa (Venter *et al.,* 2003a). The study area was selected because of its geographic location where good lucerne production is possible throughout the year. A rectangular area of 160 m X 140 m was demarcated as the experimental plot. The lucerne stand was two years old when the study commenced and was irrigated with a sprinkler irrigation system. Seventy-two sampling points 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.

Harvesting was done by cutting above-ground plant parts at an early flowering stage within a 0.6 m square at each of the sampling points and weighing to determine green biomass yield. Yield was determined on six occasions: June, August, September, October and November 2001 and again in February 2002. Mean yields per harvest were calculated from data of all sampling points. Whole plant samples from the June (winter) and February (summer) harvests were analysed for calcium (Ca), magnesium (Mg), phosphate (P) and potassium (K) content using standard methods (Agri Laboratory Association of Southern Africa, 1998). Soil samples taken in June 2001 at the sampling points were analysed for exchangeable K, Ca, Mg and sodium (Na), P status, 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.*, 2003a). Nitrogen (N) was not considered as it varies spatially with a very short correlation length (Cahn, Hummel & Brouer, 1994) and because of analytical cost considerations.

4.3.2 Statistical methods

For the purpose of this paper, two soil properties (Mg and K content) were included to illustrate the influence of soil properties on plant element uptake. The spatial relations between plant element uptake and soil properties are reported elsewhere (Venter, Beukes, Claassens & Van Meirvenne, 2003b). Descriptive statistical analyses were performed to obtain information on the frequency distribution, standard deviation and coefficients of variation of the plant and soil chemical data and yield. All properties displayed normal distributions and no transformations were necessary. A correlation matrix was developed to establish the linear correlations between the plant and soil elements, as well as biomass yield, after which an all-possible regression analysis was performed to measure the extent to which the uptake of nutrients influenced yield of the lucerne stand. A two-sample t-test (Snedecor & Cochran, 1967) was used to indicate statistical differences between the concentrations of plant nutrients, as well as between the various yields of the stand when comparing the winter and summer growing seasons.

Geostatistical analyses were performed to generate maps of the spatial variation of the plant and soil properties, as well as yield (Hunt, 2002). All the properties were normally distributed and standard semi-variograms and ordinary kriging were used to generate the estimated values. All estimates were contoured and mapped (Golden Software Inc., 1995) to illustrate the spatial variability of properties.

4.4 Results and Discussion

Table 4.1 shows the mean concentration of the nutrients Ca, Mg, P and K in the plants, as well as the Mg and K contents of the soil, and indicates that lucerne has a higher uptake of K than of the other nutrients. According to Lanyon and Griffith (1988), lucerne reflects a degree of luxury consumption of K, which means that not all the K removed in the crop is essential for plant growth. The observed mean nutrient concentrations in the plants are, according to Reuter and Robinson (1997), in the "adequate" to "high" range, although there were some spots in the field, especially for K, that showed deficiencies. The correlation matrix (Table 4.2) shows weak linear correlations between the plant elements and yield while stronger correlations exist between the soil properties and both the plant elements and yield. Using all the plant elements, an all-possible regression analysis indicated that a model that included all four elements could explain only 18 % of the variation in yield of the June harvest and 29 % of the variation in yield of the February harvest (Table 4.3).

Table 4.1 The statistical description of plant and soil properties.

Plant properties (%)		**Min.**	**Max.**	**Mean**	**Median**	**Std. Dev.**	**CV**
June 2001	Ca	0.92	1.8	1.35	1.34	0.18	0.13
	Mg	0.2	0.47	0.32	0.32	0.05	0.17
	P	0.18	0.40	0.31	0.31	0.04	0.13
	K	1.30	3.49	2.22	2.28	0.39	0.18
February 2002	Ca	0.86	1.93	1.43	1.43	0.24	0.16
	Mg	0.24	0.80	0.45	0.46	0.10	0.23
	P	0.12	0.52	0.29	0.31	0.09	0.31
	K	0.62	3.02	1.75	1.74	0.42	0.24
Yield (t ha^{-1})							
2001	June	1.59	10.72	5.69	5.42	2.03	0.36
	August	3.00	18.22	9.55	9.35	2.75	0.29
	September	3.30	22.42	11.61	11.11	4.49	0.39
	October	3.39	18.00	10.37	10.45	2.90	0.28
	November	2.54	15.99	8.66	8.46	2.83	0.33
2002	February	2.07	16.94	9.65	9.91	3.49	0.36
Soil properties (mg kg^{-1})							
June 2001	Mg	399	1917	1116	945	451	0.40
	K	94	468	222	221	65	0.30

Table 4.2 The correlation matrix of plant and soil properties and lucerne yield.

		Plant analysis - June 2001					*Plant analysis February - 2002*				
		Ca	**Mg**	**P**	**K**	**Yield**	**Ca**	**Mg**	**P**	**K**	**Yield**
Plant analysis – June 2001	**Ca**	1									
	Mg	0.05	1								
	P	0.38	-0.02	1							
	K	0.08	-0.61	0.07	1						
	Yield	0.26	-0.21	0.23	-0.02	1					
Soil	**Mg**	-0.30	0.49	-0.23	-0.20	-0.62					
	K	-0.15	-0.08	-0.12	0.45	-0.31					
Plant analysis – February 2002	**Ca**						1				
	Mg						0.28	1			
	P						0.29	0.57	1		
	K						0.07	0.02	0.44	1	
	Yield						0.21	-0.40	-0.15	-0.06	1

Table 4.3 Regression models including all leaf elements.

Harvest	Variables	% Variance explained (r^2)
June 2001	Ca, Mg, P, K	18
February 2002	Ca, Mg, P, K	29

A two-sample t-test indicated that there are highly significant differences between winter and summer values of the four elements, as well as yield (Table 4.4). These results appear to contradict the similarities in spatial variations to be discussed in Figures 4.2a to 4.2i. However, it must be borne in mind that classical statistical procedures, such as those used to obtain the results in Table 4.4, ignore any spatial correlations between field properties. Lucerne, unlike many tree species, has no true physiological rest period (McKenzie, Paquin & Duke, 1988), although it may become dormant to span unfavourable periods caused by cold, heat or drought. Yield increased during the spring months and reached its peak in September, after which it decreased into summer (Figure 4.1). According to McKenzie *et al.* (1988) this decline in production of lucerne during hot weather is commonly referred to as the "summer slump". A number of studies have been done on this phenomenon, which have resulted in several explanations. Fick *et al.* (1988) quote several studies that *inter alia* suggest (1) a combination of changes in temperature, photoperiod and water deficit, and (2) the association of shorter growth intervals and faster phenological development in summer, as causes for the summer yield decline.

Table 4.4 A two-sample t-test between the winter and summer plant analyses and lucerne yield.

	Mean plant properties				
	Ca (%)	**Mg (%)**	**P (%)**	**K (%)**	**Yield (t ha^{-1})**
June 2001	1.35	0.32	0.31	2.22	5.69
February 2002	1.43	0.45	0.29	1.75	9.65
t Value	-2.16*	-13.84***	3.13**	10.31***	-12.50***

t(0.001)(160 d.f.) = 3.29***; t(0.01)(160 d.f.) = 2.58**; t(0.05)(160 d.f.) = 1.96*

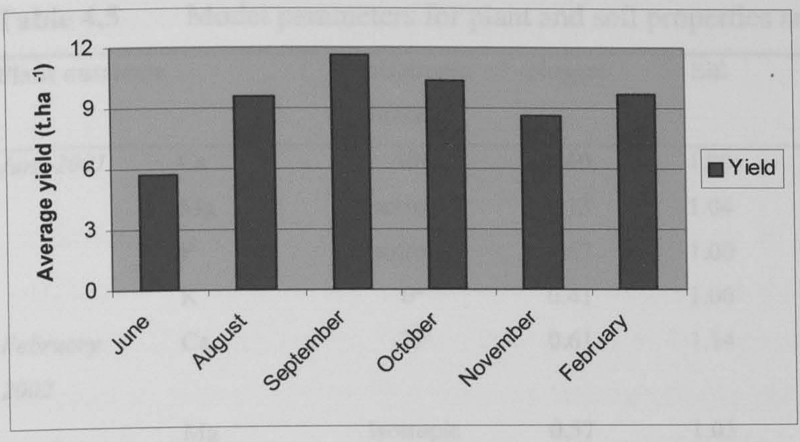


Figure 4.1 Mean yield of six harvests from June 2001 (mid-winter) to February 2002 (summer).

4.4.1 Spatial analyses

The field has a slight northeasterly slope of approximately 2 % (Venter et al., 2003a). The semi-variograms and spatial maps of plant and soil properties are given in Figure 4.2 and those of yield in Figure 4.3. Model parameters for plant and soil properties and yield are given in Table 4.5. In the case of anisotrophy, two ranges are indicated in the latter table. All the semi-variograms reached an upper boundary, i.e. a sill at a certain lag distance or range. The range is reflected as the maximum separation distance for which sample pairs remain correlated (Webster & Oliver, 2000). In practical terms this means that as spatial variability increases, the range decreases. The majority of winter plant Ca values occurred in the 0.70 – 1.20 % and 1.20 – 1.40 % classes, resulting in relatively low spatial variation (Figure 4.2a). However, in summer, spatial variability of plant Ca increased as Ca uptake increased, with a majority of values in the higher 1.40 – 1.60 % class, leaving two troughs of lower values (1.20 – 1.40 % class) (Figure 4.2b). The increase in spatial variability of summer Ca values is also reflected in the semi-variograms having a shorter range and a higher nugget variance (Table 4.5; Figures 4.2a & 4.2b). When comparing Figures 4.2a and 4.2b, some similarities are discernable between the spatial winter and summer plant Ca values. For example, ridges of high Ca values exist on both maps along the western border and the northern side. A trough of low values is also evident along the upper eastern border.

Table 4.5 Model parameters for plant and soil properties and yield.

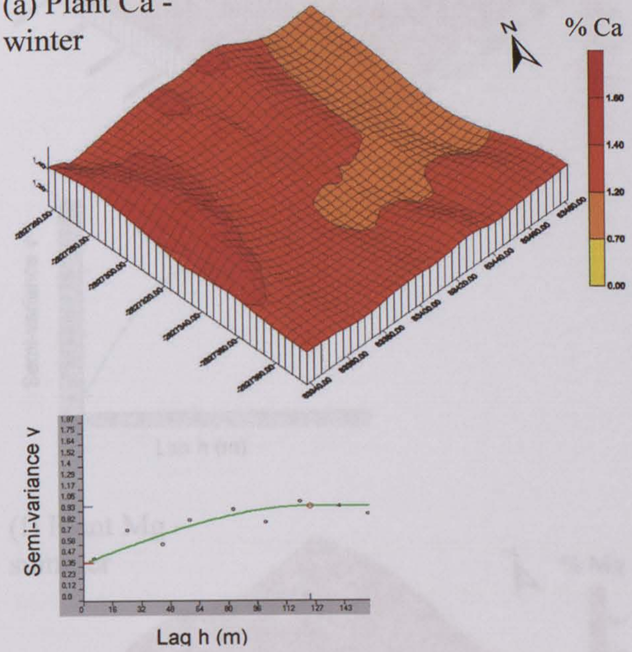
Plant nutrients		Anisotropic direction	Nugget	Sill	Long range (m)	Short range (m)
June 2001	Ca	40º	0.40	1.00	125	55
	Mg	Isotropic	0.13	1.04	61	-
	P	Isotropic	0.67	1.00	74	-
	K	0º	0.41	1.00	95	59
February 2002	Ca	20º	0.61	1.14	110	45
	Mg	Isotropic	0.57	1.05	86	-
	P	Isotropic	0.86	1.10	45	-
	K	40º	0.33	1.00	57	32
Soil nutrients						
	Mg	Isotropic	0.18	0.99	104	-
	K	Isotropic	0.17	0.82	75	-
Yield						
2001	June	140º	0.34	0.99	134	43
	August	120º	0.47	0.99	192	48
	September	120º	0.26	1.00	76	40
	October	Isotropic	0.44	0.99	92	-
	November	140º	0.32	0.99	122	32
2002	February	Isotropic	0.09	1.03	30	-

Unlike plant Ca, spatial plant P exhibits higher values in winter than in summer (compare Figures 4.2c & 4.2d), with summer P also showing higher variability. The lower summer P values may be the result of the so-called "dilution factor" because of the larger summer biomass yields (Figure 4.1; Table 4.1). There is little resemblance between winter and summer spatial values, although a trough (Figure 4.2c) and a partial trough (Figure 4.2d) of low values are discernable in an east-west direction in the centre of the field. The winter and summer spatial variation of plant Mg (Figures 4.2e & 4.2f) also bears some resemblance, with similar patches of high and low values along the northwestern and southeastern borders, respectively. Winter Mg values are also lower than summer values. Although variable in nature, the winter or summer plant Ca, P and Mg were above the deficiency values of Reuter and Robinson (1997) (Ca < 0.70; P < 0.20; Mg < 0.20 %). Although the range for Mg in the summer is slightly longer than in winter, the nugget for the summer analysis is much higher (Table 4.5). The bigger nugget variance is associated with spatially dependent variation occurring over smaller distances than the smallest sampling interval and measurement error (Webster & Oliver, 2000) (Table 4.5; Figures 4.2e & 4.2f). The estimate map of soil Mg (Figure 4.2g) shows a very good resemblance to that of the plant Mg in both winter and summer (Figures 4.2e & 4.2f). Table 4.2 shows that there is a relatively high correlation between soil and plant Mg ($r = 0.49$), as well as K ($r = 0.45$), although there is not such a clear visual resemblance between the spatial soil and plant K (compare Figures 4.2j with 4.2h and 4.2i). The high correlations may be due to the high uptake rate of both elements through the plant membrane and a high mobility throughout the entire plant. The winter and summer spatial values for plant K also bear some similarity (compare Figures 4.2h & 4.2i) with a major increase in spatial variability (and a decease in range) in summer plant K. Summer plant K values were much lower than winter values, with areas of K deficiency (K < 1.75 %: Reuter & Robinson, 1997) in both seasons, but with very marked areas of deficiency during summer. The lower summer K values may also be due to a "dilution effect" caused by the more vigorous summer plant growth. In work reported previously, a model for the prediction of K uptake by lucerne consisted of factors such as the exchangeable Ca, K and silt content of the soil, as well as the amounts of Ca and Mg taken up by the lucerne, and explained 58 % of the variation in plant K for this field (Venter et al., 2003b). It was concluded that the uptake of plant nutrients, such as K, is not solely dependent on the availability of the nutrient in the growth medium, but is influenced by various other factors as well.

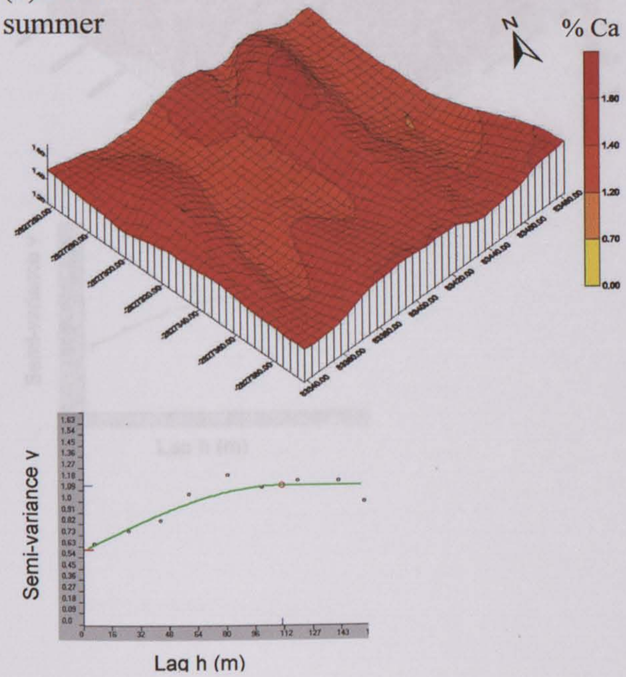
Temporal and spatial variations in lucerne yield are depicted in Figures 4.3a to 4.3f. The semi-variograms indicate that the direction of anisotrophy stays the same throughout the year except in the case of October and February (Figures 4.3d & 4.3f) where no preferred long and short-range directions could be identified and isotropic semi-variograms were modelled. Areas of smaller and larger yields generally vary across the six harvesting incidents with a trough of lower yields discernable towards the northwestern side of the stand for each yield map. The pattern of lowest and highest yields in June and September, respectively, can be observed in Figures 4.3a and 4.3c (see also Figure 4.1). Unlike the results of Frogbrook *et al.* (2002), the shapes of the variograms were dissimilar, yielding for example, highly variable ranges of spatial correlation (Figures 4.3a – 4.3f; Table 4.5). A direct implication of this finding is that sampling intensity should be varied depending on the time of sampling. There is a clear visual resemblance between the plant K maps

(Figure 4.2h & 4.2i) and the matching yield maps (Figure 4.3a & 4.3f). As previously mentioned, areas of deficient plant K were evident and apparently this deficiency was the major cause of spatial variation in yield.

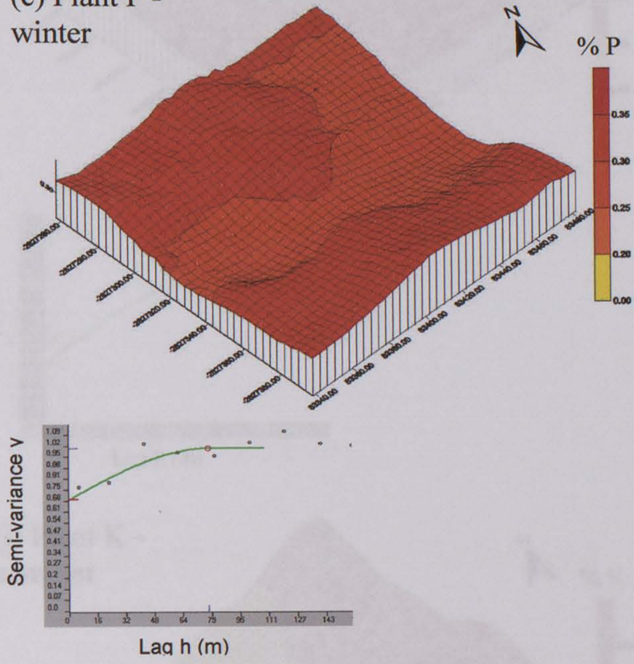
(a) Plant Ca - winter



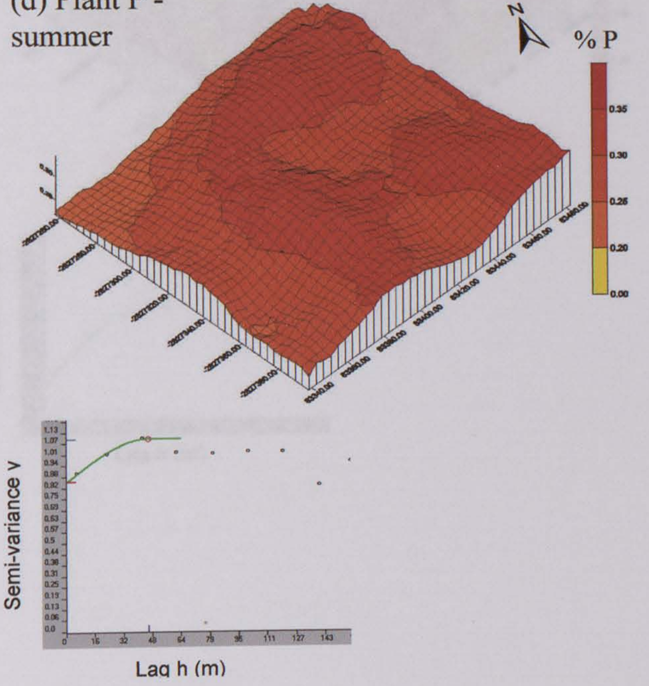
(b) Plant Ca - summer



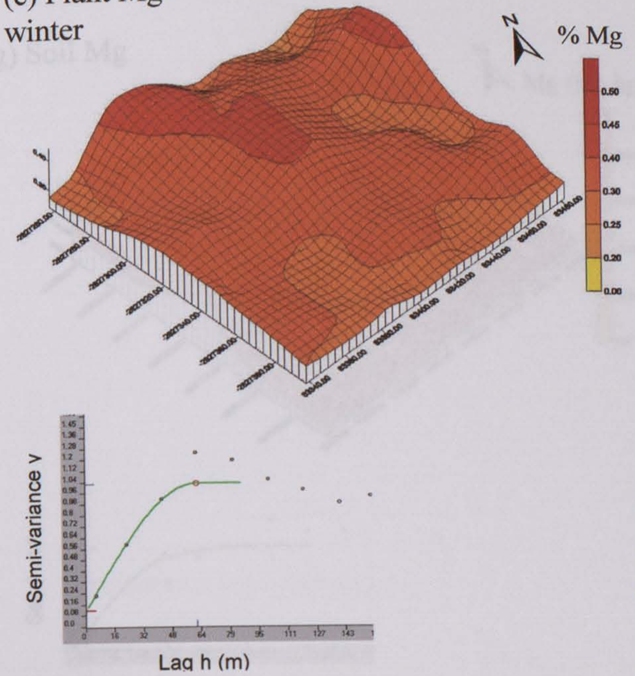
(c) Plant P - winter



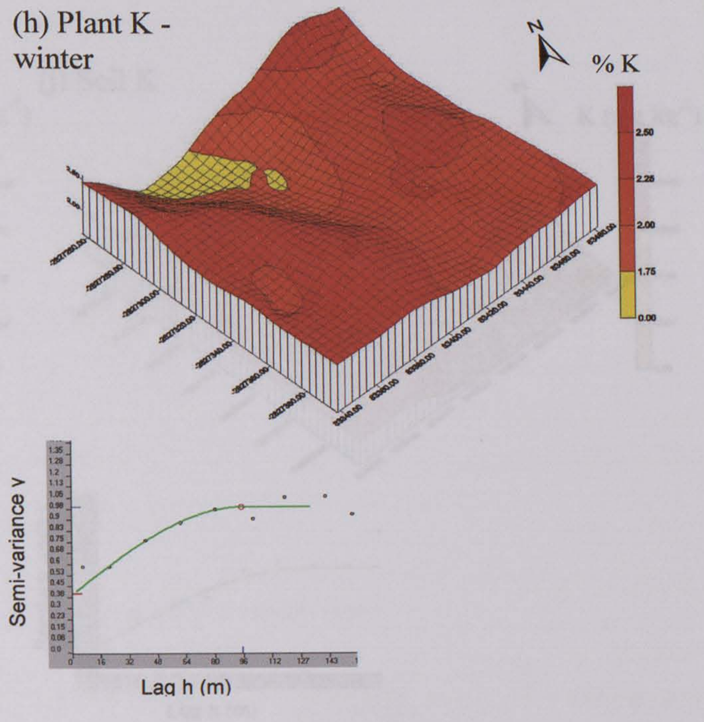
(d) Plant P - summer



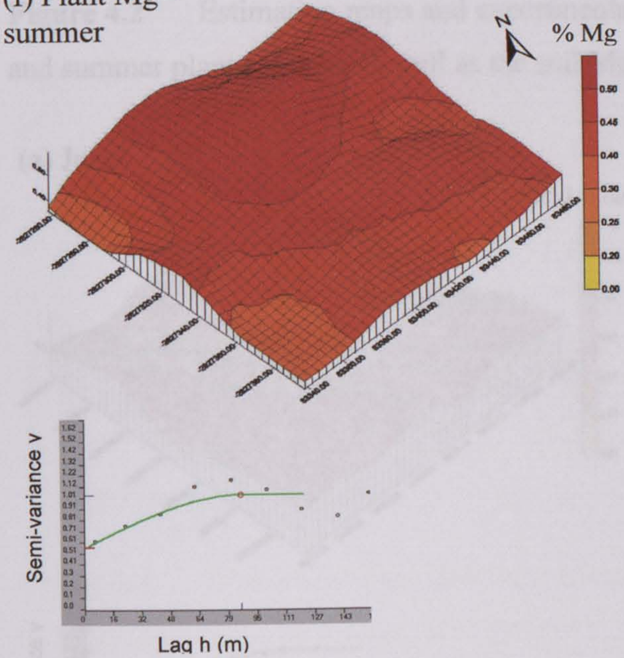
(e) Plant Mg - winter



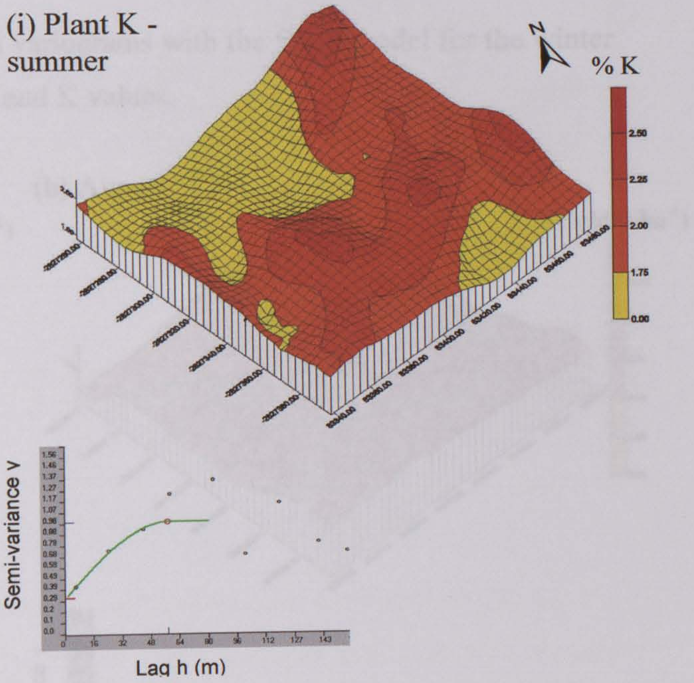
(h) Plant K - winter

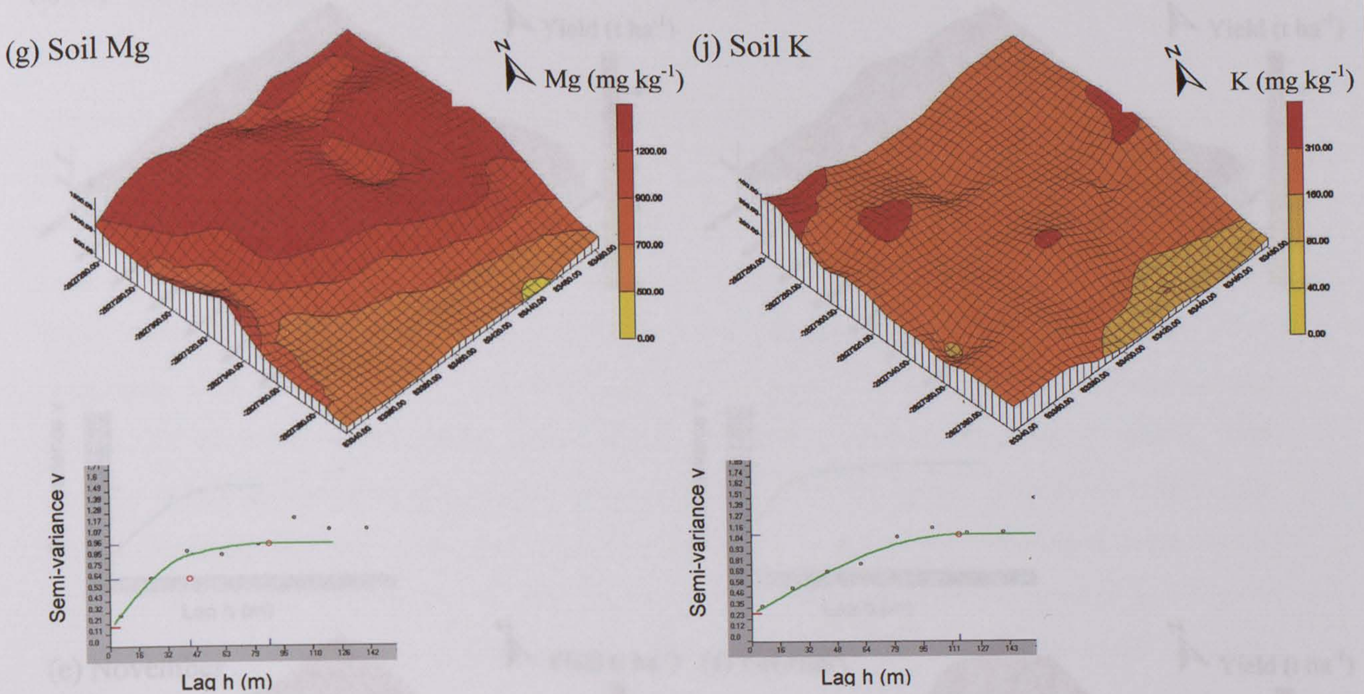


(f) Plant Mg - summer



(i) Plant K - summer

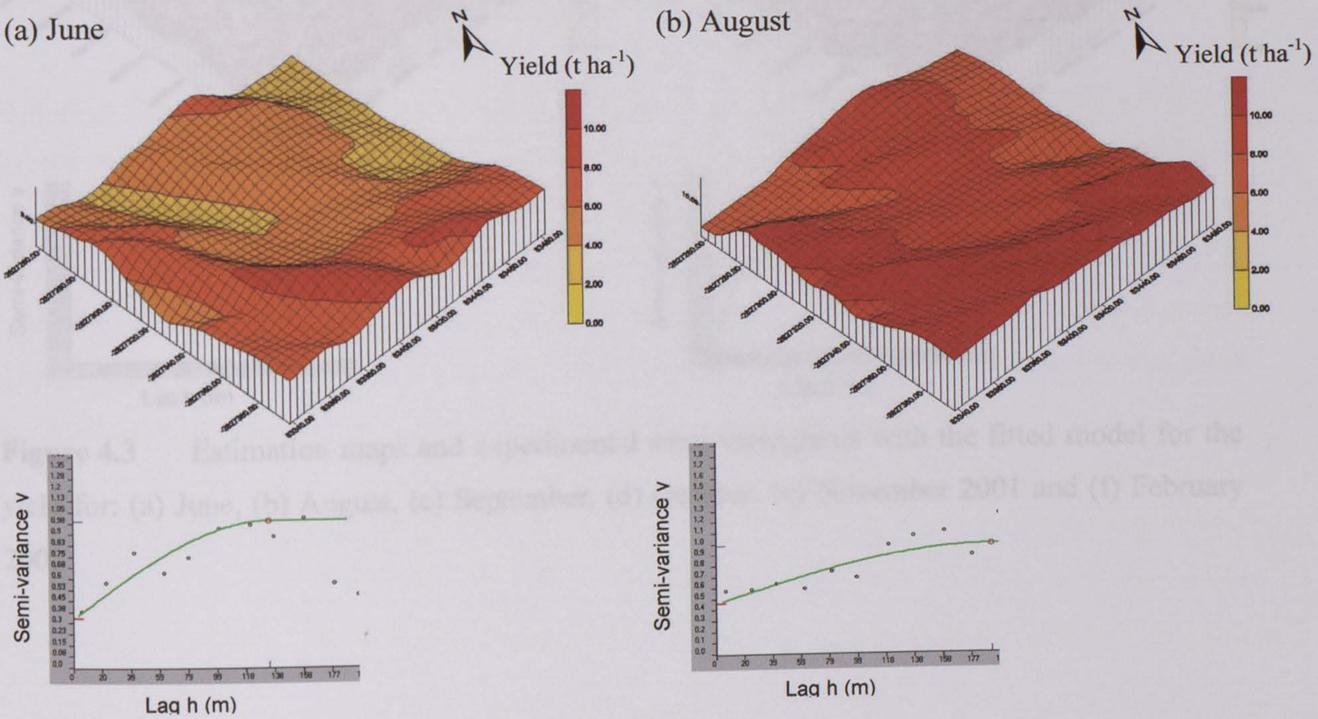




(g) Soil Mg

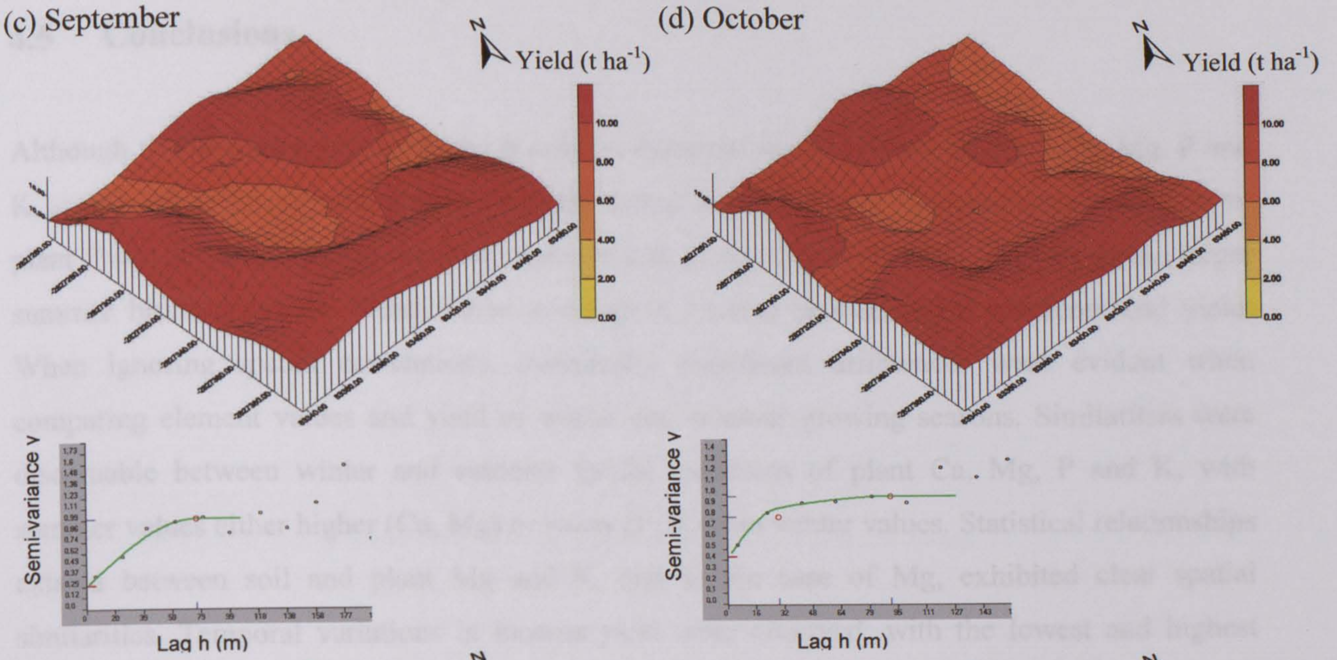
(j) Soil K

Figure 4.2 Estimation maps and experimental variograms with the fitted model for the winter and summer plant analyses as well as the soil Mg and K values.



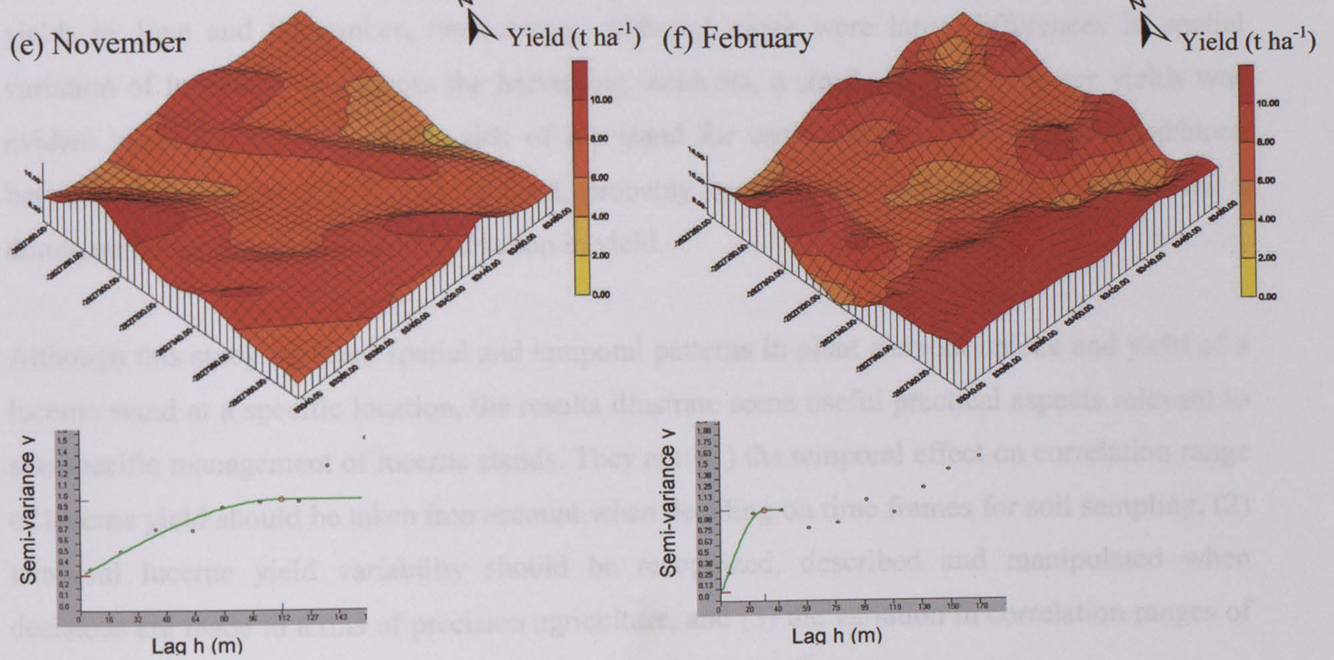
(a) June

(b) August



(c) September

(d) October



(e) November

(f) February

Figure 4.3 Estimation maps and experimental semi-variograms with the fitted model for the yield for: (a) June, (b) August, (c) September, (d) October, (e) November 2001 and (f) February 2002.

4.5 Conclusions

Although the lucerne stand contains on average adequate concentrations of plant Ca, Mg, P and K, areas of K deficiency did occur in the field during both the winter and summer seasons. Lower plant P and K values during summer could be due to the "dilution effect" exerted by the larger summer biomass yields. Weak linear correlations existed between plant elements and yield. When ignoring spatial correlations, statistically significant differences were evident when comparing element values and yield of winter and summer growing seasons. Similarities were discernable between winter and summer spatial variations of plant Ca, Mg, P and K, with summer values either higher (Ca, Mg) or lower (P, K) than winter values. Statistical relationships existed between soil and plant Mg and K, and in the case of Mg, exhibited clear spatial similarities. Temporal variations in lucerne yield were observed, with the lowest and highest yields in June and September, respectively. Although there were large differences in spatial variation of lucerne yields across the harvesting incidents, a similar trough of lower yields was evident towards the northwestern side of the stand for each yield map. A clear resemblance between spatial plant K and yield existed, probably because the deficiency in plant K was a dominant factor in causing spatial variation in yield.

Although this study revealed spatial and temporal patterns in plant element uptake and yield of a lucerne stand at a specific location, the results illustrate some useful practical aspects relevant to site-specific management of lucerne stands. They are: (1) the temporal effect on correlation range of lucerne yield should be taken into account when deciding on time frames for soil sampling, (2) temporal lucerne yield variability should be recognized, described and manipulated when decisions are made in terms of precision agriculture, and (3) the variation in correlation ranges of the various plant elements should be considered in plant sampling patterns.