SEÇÃO VI - MANEJO E CONSERVAÇÃO DO SOLO E DA ÁGUA

CHEMICAL CHANGES IN ARGISOLS UNDER IRRIGATED GRAPE PRODUCTION IN THE CENTRAL SÃO FRANCISCO RIVER VALLEY, BRAZIL(1)

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SUMMARY

This study compares the chemical composition of the solution and exchange complex of soil in a 3-year-old irrigated vineyard (*Vitis vinifera* L., Red Globe cultivar) with that of adjacent clearing in the native hyperxerophyllic 'caatinga' vegetation. The soils are classified as Plinthic Eutrophic Red-Yellow Argisol; according to Soil Taxonomy they are isohyperthermic Plinthustalfs. Detailed physiographic characterization revealed an impermeable gravel and cobble covering the crystalline rocks; the relief of this layer was more undulating than the level surface. Significant higher concentrations of extractable Na, K, Mg and Ca were observed within the vineyard. Lower soil acidity, higher Ca/Mg ratios, as well as lower sodium adsorption and Na/K ratios reflected additions of dolomitic lime, superphosphate and K-bearing fertilizers. As the water of the São Francisco River is of good quality for irrigation (C1S1), the increases in Na were primarily attributed to capillary rise from the saline groundwater table. None of the soil in the study area was found to be sodic. About 62% of the vineyard had an Ap horizon with salinity levels above 1.5 dS m^{-1} (considered detrimental for grape production); according to average values for this horizon, a potential 13% reduction in grape production was predicted. Differences in chemical composition in function of distance to the collector canals were observed in the clearing, but not in the vineyard. The influence of differences in the elevations of the surface and impermeable layers, as well as pediment thickness, was generally weaker under irrigation. Under irrigation, soil moisture was greater in points of convergent surface waterflow; the effect of surface curvature on chemical properties, though less consistent, was also stronger in the vineyard.

Index terms: vineyard, physiography, moisture content, exchangeable cations, electrical conductivity, soluble cations, sodicity, acidity.

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RESUMO: *MUDANÇAS QUÍMICAS EM ARGISSOLOS SOB VITICULTURA IRRIGADA NO VALE DO MÉDIO RIO SÃO FRANCISCO*

*O estudo compara a composição química da solução e o complexo de troca catiônica de Argissolos Vermelho-Amarelos eutróficos plínticos (isohyperthermic Plinthustalf em Soil Taxonomy) com cultura irrigada de uva (*Vitis vinifera *L., cultivar "Red Globe"), com solos similares de área contígua, desmatada de sua vegetação natural de caatinga hiperxerófila. Levantamento fisiográfico da área caracterizou os relevos de superfície e subsuperfície e as condições de microvariações em direcionamento e curvaturas do relevo superficial. O relevo subsuperficial, mais ondulado que o de superfície, é definido pela oscilação de camada impermeável com espessura variável, constituída de cascalhos e calhaus de quartzo, base do pedimento que recobre o embasamento cristalino na região. O efeito das curvaturas do relevo superficial foi evidente na maior umidade do solo da área irrigada e menos consistente em suas propriedades químicas. Grande parte dos acréscimos observados nos teores de Ca, Mg e K, extraídos por* NH_4Cl*, foi atribuída ao manejo dos solos com irrigação, fertilizações e corretivos; acréscimos nos teores de Na indicam ascensão capilar de água do lençol freático à razão aproximada anual de 60* $L\ m^{-2}$*. Não foram detectados teores críticos de sódio, mas foram observados horizontes salinos, empecialmente nos Ap, estimando-se que devem contribuir para um decréscimo de cerca de 13% no potencial produtivo de uvas. Decréscimos em acidez dos solos e acréscimos nas razões Ca/Mg refletiram adições de calcário dolomítico e fertilizantes fosfatados. Foram, também, observadas variações em propriedades dos solos conforme a distância para o canal de drenagem, atribuídas à deposição de detritos durante escavações deste canal.*

Termos de indexação: videira, fisiografia, umidade do solo, cations trocáveis, condutividade elétrica, cátions solúveis, sodicidade, acidez.

INTRODUCTION

Irrigated grape (*Vitis vinifera* L.) production is one of the most economically important agricultural activities in the Central São Francisco River Valley. Harvest normally occurs twice a year: in July or August after 120-130 days of vegetative growth and in late December after 100 days of vegetative growth (Lakatos, 1995). But, given the favorable climatic conditions, up to two and one-half productive cycles can be induced each year (Magalhães, 1995); in such situations, annual production varies from 34 to 40 t ha^{-1}.

At planting, the soils are limed and fertilized according to an initial soil analysis. Subsequent soil management is based on production cycles (Magalhães, 1995); soil analyses are conducted every second year, but recommendations are adjusted according to foliar analysis done during every flowering. Applications are normally divided throughout the production cycle: eight days before pruning, at budding (20 days), after thinning (45-50 days), then again at 70 and 90 days after pruning. The traditional fertilizers applied are urea and superphosphate as well as potassium chloride, which, due to chloride toxicity, is now being substituted by potassium sulfate. As indicated by Pereira & Cordeiro (1987), the São Francisco River water presents no salinity or sodicity hazards for irrigation (classified as C1S1, according to Richards [1954]).

Pereira & Cordeiro (1987) evaluated the impact of such grape production on certain chemical properties of Vertisols. After 17 years, the surface horizon had suffered a decrease in pH, an increase in electrical conductivity and exchangeable K, but only minimal changes in exchangeable Ca, Mg and Na. Despite these changes, production had not been significantly jeopardized. According to Maas (1986), however, the growth of grapes will be decreased at a rate of 9.6% per dS m^{-1}, for levels of salinity above 1.5 dS m^{-1}.

Argisols (formerly termed Podzolic soils in the Brazilian System of Soil Classification) are characterized by an accentuated difference in texture from the A to B horizons, but are variable in color, thickness, texture, drainage, stoniness and relief (Burgos et al., 1998). Within the Petrolina area of the State of Pernambuco, they are developed on a post-Cretaceous sandy to clayey pediment, covering pre-Cambrian magmatic and metamorphic rocks (Gomes, 1990), which generally varies in depth from 1.5 to 2 m and offers high potential for irrigation (CODEVASF, 1976). According to studies by Santos et al. (2001) and Heck et al. (2001), the introduction of irrigated grape production has caused significant changes in the lateral and vertical variability of soil texture and moisture retention as well as organic carbon content and nature of free Fe and Al oxides.

This work examines how the intense management practices associated with irrigated grape production have influenced the spatial variability of salinity and acidity of these Argisols. Understanding the cause of this variability is fundamental to developing suitable soil monitoring and management schemes. A similar study was conducted by Heck et al. (2001) under irrigated mangos. Recognizing the impact that variations in local physiography can have on soil properties (Pennock et al., 1987; Pennock & De Jong, 1991), results are evaluated with respect to surface landform, pediment thickness as well as elevation of the impermeable (actually gravel and cobble) layer. Special consideration is also given here to the influence of distance to collector canals and grapevines.

MATERIAL AND METHODS

The area selected for this study is 'Fazenda Garibaldina' (9° 4' S, 40° 8' W), a large grape plantation located in the municipality of Lagoa Grande, Pernambuco. According to the Köeppen classification system, the climate of the area is Bswh', very hot (mean annual temperature 26°C) and semi-arid; the majority of the annual precipitation (400 mm) falls during the winter season (Jacomine et al., 1973; CODEVASF, 1976). The natural vegetation is hyperxerophyllic 'caatinga'. The soils are developed on level medium over clayey textured pediments, and are classified as Argissolo Vermelho-Amarelo eutrófico plíntico (Plinthic Eutrophic Red-Yellow Argisol) (EMBRAPA, 1999). According to Soil Taxonomy, they are classified as isohyperthermic Plinthustult (Soil Survey Staff, 1998). Selected physical characteristics of this soil are provided in table 1. At the time of sampling (April, 1994), the area consisted of a 3 year-old irrigated vineyard (V*itis vinifera* L., Red Glode cultivar), with approximately 3 x 3.5 m plant spacing, adjacent to a recent clearing in the native 'caatinga' vegetation. Artificial drainage was accomplished by collector canals about 1.3 m deep, 0.5 m wide and spaced by 30 m.

Table 1. Selected physical characteristics of the soil studied[(1)]

Horizon	Depth	Texture	Bulk density	0.3 Mpa moisture retention
	cm		Mg m^{-3}	g kg^{-1}
Ap	0-21	Sandy Loam	1.54	111
Btf1	21-68	Sandy Clay	1.44	165
Btf2	68-111	Sandy Clay	1.50	170
Btf3	111-143	Sandy Clay	1.64	164
Btf4	143-193	Sandy Clay	1.70	176

(1) Based on Souto Maior (1996).

At planting time, approximately 55 kg ha^{-1} of urea, 504 kg ha^{-1} of superphosphate and 44 kg ha^{-1} of potassium chloride had been applied (data based on personal communication with plantation agronomist at sampling time). During subsequent production cycle, approximately 154 kg ha^{-1} of urea, 132 kg ha^{-1} of superphosphate and 395 kg ha^{-1} of potassium sulfate were usually applied as fertigation, as well as 50 kg of dolomitic lime per row (approximately 100 m long). Normally, about 6 mm of irrigation water was applied daily during production, though adjacent lines were activated on an eight-day cycle.

Prior to sampling, a 12 x 12 grid was demarcated; roughly 60% in the vineyard and 40% in the clearing. While the east-west distance between points was 10 m, the north-south distance varied slightly since they were placed in every third row of vines (about 10 m); the total area covered was 1.21 ha. Thus, the distance between sampling points and grapevines varied from 0.3 to 1.8 m; one half occurred at less than 1 m distance. A theodolite was used to measure the surface elevation of each node, relative to a local datum (lowest point measured). The depth to the underlying impermeable layer was also determined through auger holes at each node point.

Contour maps of soil properties were generated from the elevation data, by the 'moving weighted least squares' gridding method of the software MacGridzo (1990). The surface of the study area is plan with an overall slope of less than 1% (Figure 1). Though the pediment overlying the impermeable layer was less than 0.6 m thick in the southeast quadrant, it exceeded 1 m in most of the study area. The elevation of the underlying impermeable layer is also not significantly different in the two sub-areas (Figure 2), but it is more undulating than the surface and contains several depressions, some of which would not be completely drained by the collector channels.

Using the computer program TOPO (Pennock, 1993), the following primary landscape attributes were calculated for each 3 x 3 array of nodes: slope and its derivative (profile curvature), as well as the aspect and its derivative (plan curvature). Of the 30 points analyzed in the clearing, 14 present concave plan curvature and 13 concave profile curvature. In the vineyard, 33 of the 50 analyzed points exhibit concave plan curvature and 24 concave profile curvature. Though the slopes of individual landscape elements generally revealed a net southward waterflow pattern, several points of convergence and potential for ponding were evident.

Soil samples were obtained from each of the central 100 nodes, using a 9 cm cup auger, from three depths: 0-0.3, 0.3-0.6 and 0.6-0.9 m; these corresponded approximately to the Ap, Btf1 and Btf2 horizons (Souto Maior, 1996). A sample of the irrigation water was also collected for chemical analysis. Following gravimetric determination of field moisture, the soil samples were air dried and crushed to pass a 2 mm sieve. Electrical conductivity was determined in water (1:1 and saturated paste) extracts, pH in 1 mol L^{-1} KCl and water extracts by direct potentiometry, and extractable bases were obtained by 24 hr reaction with 1 mol L^{-1} NH_4Cl solution in a 1:10 ratio. The concentration of soluble and extractable cations were determined by atomic emission (Na and K) or atomic absorption (Mg and Ca) spectroscopy. Sodium adsorption ratios (SAR) were calculated from cation concentrations according to the equation:

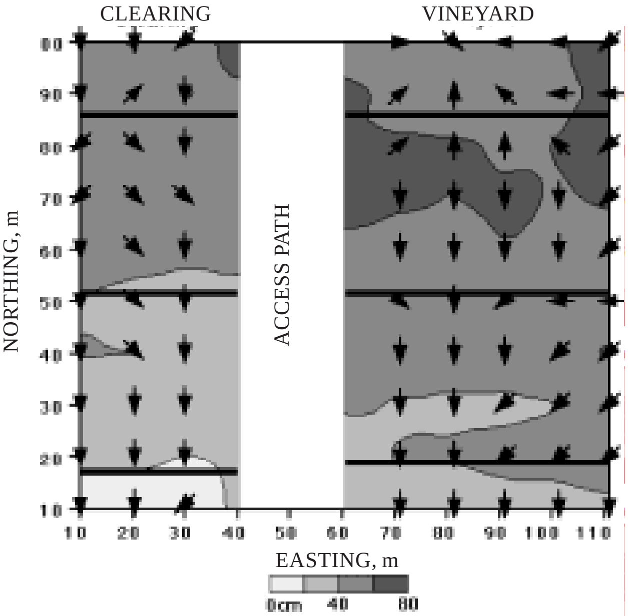

Figure 1. Surface elevation map of the Fazenda Garibaldina study site. The lowest relative elevation measured is taken as the local datum. Arrows indicate slope direction calculated from the digital elevation model by the program TOPO (see text); thick parallel lines represent collector canals.

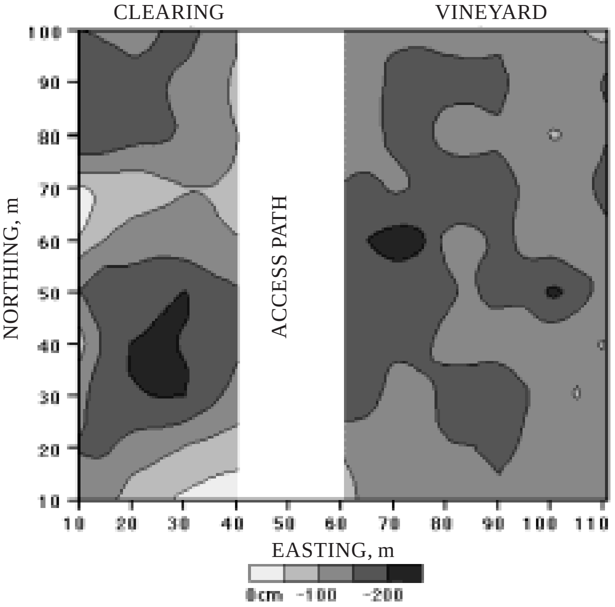

Figure 2. Elevation map of the subsurface impermeable layer. The local datum is the same as in figure 1.

$$SAR = [Na] / ([Ca] + [Mg])^{0.5} \qquad (1)$$

where [ ] signifies solution concentration in mmol L^{-1}.

Statistical analysis of differences were conducted using the non-parametric tests Wilcoxon Signed-Rank (for comparison of values in the two horizons), Mann-Whitney U (for comparison of values in groupings of values based on sub-area, distance from grapevine stems and surface curvature) and Kruskal-Wallis (for comparison of groupings of values based on distance to the collector canals and quartiles of other properties) of the software 'STATVIEW SE + GRAPHICS' (1988). The Spearman rank correlation test was used to obtain coefficients of correlation (r_s) between groups of data. In general, statistical probabilities of up to 10% were considered to be significant; unless specifically indicated, however, the level was less than 5%. The use of less rigorous probability levels (up to 20%) is well accepted in landscape-based studies (Pennock et al., 1994; Corre et al., 1996; Beckie et al., 1997).

RESULTS AND DISCUSSION

Production inputs

The water sample obtained from the active irrigation system was slightly less saline and sodic than the average reported for the São Francisco River (Table 2). Assuming 230 days of irrigation per year (Lakatos, 1995), about 4.100 L m^{-2} would have been applied in the three years since planting. Based on the average composition of the river water, this would have contributed about 0.41 mol m^{-2} of Na, 0.25 of K, 0.41 of Mg and 0.78 of Ca to the soil.

Superphosphate fertilizer applied to soils in Pernambuco generally contains 18% Ca and the potassium chloride fertilizer contains 48% K (Cavalcanti, 1998). Therefore, approximately, about 0.23 mol m^{-2} of Ca and 0.06 mol m^{-2} of K would have been applied at planting. Assuming further that the potassium sulfate fertilizer contains 40% K and 0.6% Mg, a total of 0.36 mol m^{-2} of Ca, 2.67 mol m^{-2} of K and 0.06 mol m^{-2} of Mg would have also been applied as fertigation during the first three production years. Since the dolomitic lime contains about 18% Ca and 12% Mg, an additional 1.300 mol of Ca and 900 mol of Mg would have been applied along each row. The urea applied during this period had the potential to neutralize 0.08 kg m^{-2} of $CaCO_3$ (Cavalcanti, 1998), equivalent to about 0.09 kg m^{-2} of dolomitic lime (assuming 82% dolomite according to the Ca assay); this is much less than the lime added.

Soil moisture

The soil in the vineyard contained more moisture at all depths than that in the clearing (Table 3), regardless of distance to collector canals or grapevines. Furthermore, rows with active irrigation lines at sampling time (at 10, 30, 50, 70 and 90 m northing in the figures) contained more moisture; this difference was statistically significant for the Ap horizons. Moderate correlations in absolute ($r_s = 0.36$*) and relative ($r_s = 0.36$) moisture content were observed between the Ap and Btf2 horizons in the clearing; however, correlations in the vineyard were not significant. Apparently irrigation has had a stronger impact near the soil surface.

Table 2. Chemical composition of the São Francisco River water and irrigation water at the study site

Property	Average for São Francisco river(1)	Irrigation water
pH	7.30	7.80
EC (dS m^{-1})	0.078	0.066
Na (mmol$_c$ L^{-1})	0.10	0.03
K (mmol$_c$ L^{-1})	0.06	0.04
Mg (mmol$_c$ L^{-1})	0.20	0.10
Ca (mmol$_c$ L^{-1})	0.38	0.38
Na/K ratio	1.44	0.75
SAR (mmol$^{0.5}$ $L^{0.5}$)	0.18	0.06
Ca/Mg	1.90	3.80

(1) From Pereira & Cordeiro (1987).

In both sub-areas, the absolute soil moisture content increased with depth (Table 3). A similar trend was observed relative to field capacity only in the clearing; in the vineyard, and especially closer to the grapevines, the Ap horizon was wetter than the Btf2. This larger retention of water is likely due to a greater organic matter content near the grapevines (Heck et al., 2001). The Btf2 horizons were also generally wetter near the collector canals, possibly due to standing water in the canals. In the vineyard, the Ap horizon also contained more moisture near the collector canals but showed no difference relative to field capacity; this can be attributed to the increase in moisture retention resulting from the deposition of fine-textured material during excavation (Santos et al., 2001).

Based on quartile analysis, pediment thickness had no significant influence on the relative soil moisture content. Similarly, no difference was observed with respect to the relative elevation of the impermeable layer in the clearing. In the vineyard, however, the Ap horizon was wetter where the impermeable layer was higher; likely reflecting retarded water infiltration. Although no difference was observed with respect to relative surface elevation in the vineyard, the Btf2 horizon in the clearing was wetter in the lowest quartile of points. In contrast, significant differences due to surface curvature were observed only in the vineyard (Table 4): the points with concave plan curvature were wetter than points with convex curvature. A

Table 3. Field soil water content(1), according to sub-area as well as distance to collector canals and plants

Horizon	Clearing				Vineyard					
	All	Distance to collector canals (m)			All	Distance to collector canals (m)			Distance to plant (m)	
		0-5	5-10	10-15		0-5	5-10	10-15	0-1	1-2
Cases:	40	16	8	16	60	24	12	24	30	30
					Absolute, g kg^{-1}					
Ap	56 (25)(2) Bγ(2)	57 Baγ	60 Baβ	53 Baβ	93 (26) Aγ	102 Aaγ	92 Aabβ	85 Abγ	100 Aaγ	87 Abγ
Btf1	100 (20) Bβ	108 Baβ	98 Babα	94 Bbα	128 (17) Aβ	133 Aaβ	124 Aaα	126 Aaβ	131 Aaβ	126 Aaβ
Btf2	110 (22) Bα	125 Baα	103 Bbα	96 Bbα	140 (16) Aα	146 Aaα	125 Abα	141 Aaα	142 Aaα	138 Aaα
					Relative to field capacity(1)					
Ap	0.50 (22) Bβ	0.52 Baβ	0.48 Baα	0.49 Baα	0.86 (24) Aα	0.88 Aaα	0.83 Aaα	0.86 Aaα	0.97 Aaα	0.78 Abα
Btf2	0.64 (24) Bα	0.73 Baα	0.59 Abα	0.57 Bbα	0.77 (12) Aβ	0.80 Aaα	0.70 Abα	0.77Aabα	0.78 Aaβ	0.76 Aaα

(1) 0.3 Mpa. (2) Numbers in parentheses represent coefficients of variation. (3) Capital letters compare sub-areas; small letters, distances to grapevines; and Greek letters, horizons.

comparison of figures 3 and 1 also revealed greater moisture in points where water converges from several landscape elements.

NH_4Cl-Extractable basic cations

According to quartile analysis, none of the four basic cations (Na, K, Mg, Ca) extracted from the Ap horizon (both sub-areas) by NH_4Cl solution exhibited a significant relationship to the relative elevation of the soil surface, to the thickness of the pediment, nor to the elevation of the impermeable layer. Sodium in the Btf1 and Btf2 horizons also did not exhibit a significant relationship to these features. Greater concentrations of K did occur in the Btf2 horizon at the highest points (and vice versa) in the clearing, but not in the vineyard. In both sub-areas, the larger K concentrations were found where the pediment was thinnest and the impermeable layer was highest. Though not evident in the clearing, the highest points in the vineyard also exhibited larger concentrations of Ca in the Btf1 horizon (and vice versa), but no significant relationship to pediment thickness or impermeable layer depth. The trends observed with K and Ca are consistent with the retention of water. In contrast, Mg concentrations in the Btf1 horizons of the clearing were generally smaller where the pediment was thinnest and the impermeable layer the highest (and vice versa).

Table 4. Comparison of selected properties between landscape elements with concave and convex surface curvature

Property horizon[1]	Profile curvature			Plan curvature		
	Ap	Btf1	Btf2	Ap	Btf1	Btf2
			Concave x convex			
Water[2] Grapes	=	=	=	>	>	>
Na_{ext} Grapes	<[3]	=	=	=	=	=
Clearing	=	=	>	=	=	=
K_{ext} Grapes	<	=	=	=	=	>
Ca_{ext} Grapes	<	<	=	=	=	=
Clearing	=	=	=	<	<	=
Mg_{ext} Grapes	<	<	=	=	=	=
Clearing	<	=	=	=	=	=
Ca/Mg_{ext} Clearing	=	=	=	<	=	=
$pH_{1:1}$ Grapes	=	=	=	>	>	=
pH_{KCl} Clearing	=	<	=	=	=	=
ΔpH Grapes	=	=	=	=	>	>
pH_{sat} Grapes	<	nd	=	=	nd	>
K_{sat} Grapes	=	nd	=	>	nd	=
Clearing	=	nd	=	=	nd	>
Ca_{sat} Grapes	=	nd	<	=	nd	=
Mg_{sat} Grapes	<	nd	<	=	nd	=
Na/K_{sat} Grapes	=	nd	>	=	nd	=
Clearing	=	nd	=	=	nd	<
Ca/Mg_{sat} Grapes	<	nd	=	=	nd	=
Clearing	>	Nd	=	=	nd	=
SAR_{sat} Grapes	=	Nd	>	=	nd	=

(1) Ext = NH_4Cl-solution extractable; 1:1 = 1:1 water extracts; KCl = 1 mol L^{-1} KCl-solution extractable; sat = saturated paste extracts. (2) Soil water content at sampling time. (3) Inequality symbols indicate significant differences at $p < 10\%$; nd = not determined.

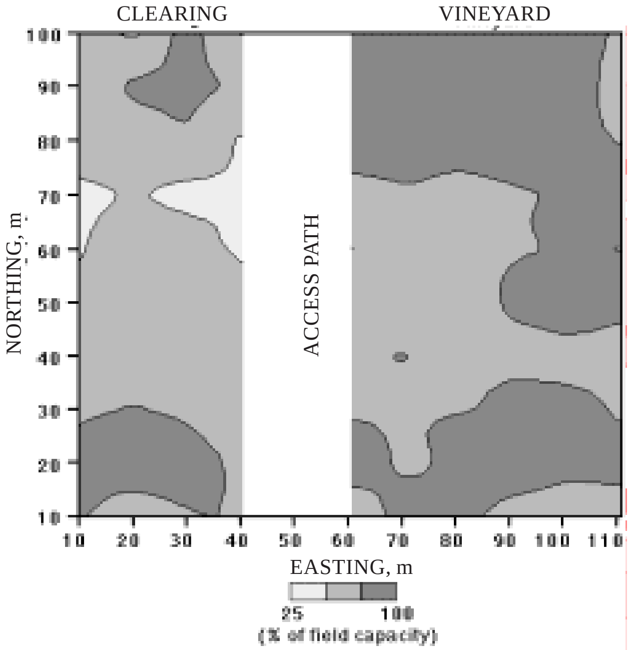

Figure 3. Ratio of actual moisture to field capacity of the Btf2 horizon at time of sampling.

A comparison of NH_4Cl-extractable cation concentrations, in function of surface curvature, also reveals trends consistent with the notion of convergence of water in concave elements (Table 4). Landscape elements with concave profile curvature and, to a lesser extent, with concave plan curvature, exhibited smaller concentrations in the Ap and Btf1 horizons; especially within the vineyard. A subsequent tendency for accumulation of monovalent cations in the Btf2 was also observed.

With the exception of K in the clearing, no significant differences were observed in NH_4Cl-extractable cation concentrations in relation to distance from the collector canals in either sub-area (Table 5). While profile trends observed for Mg (increase with depth) as well as K and Ca (decrease with depth) in the vineyard were similar to that observed in the clearing, the increase in Na with depth observed in the clearing was absent under grape production. Within the vineyard, greater cation concentrations were also consistently found closer to the grapevines; this can be attributed to both the localized application of fertilizer and extraction of soil water by plant roots.

Table 5. Average composition of 1 mol L^{-1} NH_4Cl-extractable cations, according to sub-area as well as distance to collector canals and plants[1]

Horizon	Clearing				Vineyard					
	All	Distance to collector canals (m)			All	Distance to collector canals (m)			Distance to plant (m)	
		0-5	5-10	10-15		0-5	5-10	10-15	0-1	1-2
					Na, cmol$_c$ kg^{-1}					
Ap	0.7 (74)[2] Bγ	0.7 Baβ	0.5 Baβ	0.8 Baβ	1.5 (38) Aαβ	1.6 Aaα	1.4 Aaα	1.4 Aaα	1.7 Aaαβ	1.2 Abα
Btf1	1.0 (93) Bβ [3]	1.3 Baα	0.7 Baα	1.0 Baβ	1.6 (45) Aα	1.7 Aaα	1.5 Aaα	1.5 Aaα	1.8 Aaα	1.3 Abα
Btf2	1.6 (107) Bα	1.8 Aaα	0.9 Baαβ	1.7 Baα	1.5 (60) Aβ	1.5 Aaα	1.4 Aaα	1.5 Aaα	1.8 Aaβ	1.1 Bbα
					K, cmol$_c$ kg^{-1}					
Ap	3.4 (28) Bα	3.2 Baα	3.1 Baα	3.7 Baα	9.1 (43) Aα	8.9 Aaα	10.4 Aaα	8.7 Aaα	10.8 Aaα	7.5 Abα
Btf1	2.4 (38) Bβ	2.2 Bbβ	2.1 Bbβ	2.9 Baβ	8.5 (61) Aβ	8.0 Aaβ	9.4 Aaα	8.5 Aaα	11.7 Aaα	5.2 Abβ
Btf2	1.2 (42) Bγ	1.1 Bbγ	0.9 Bbγ	1.4 Baγ	5.0 (74) Aγ	5.1 Aaγ	5.3 Aaβ	4.7 Aaβ	7.7 Aaβ	2.4 Abγ
					Ca, cmol$_c$ kg^{-1}					
Ap	17.7 (27) Bαβ	17.1Baαβ	17.5 Aaα	18.6 Baα	35.8 (55) Aα	37.2 Aaα	30.6 Aaα	37.1 Baα	46.3 Aaα	25.4 Abα
Btf1	18.3 (37) Bα	18.3 Baα	17.7 Aaα	18.6 Aaα	23.5 (48) Aβ	26.3 Aaβ	23.0 Aaα	20.9 Aaβ	27.6 Aaβ	19.3 Bbβ
Btf2	16.6 (31) Bβ	16.1 Baβ	15.8 Aaβ	17.4 Aaα	20.8 (24) Aγ	21.6 Aaγ	19.6 Aaβ	20.5 Aaβ	22.2 Aaγ	19.3 Abβ
					Mg, cmol$_c$ kg^{-1}					
Ap	5.1 (24) Bγ	5.0 Baγ	4.9 Aaβ	5.4 Aaγ	7.7 (50) Aγ	8.4 Aaγ	7.0 Aaγ	7.3 Aaγ	9.6 Aaγ	7.5 Bbγ
Btf1	7.3 (38) Bβ	7.6 Baβ	6.8 Aaα	7.1 Baβ	9.3 (43) Aβ	10.3 Aaβ	9.4 Aaβ	8.3 Aaβ	11.0 Aaβ	7.7 Bbβ
Btf2	8.7 (30) Bα	8.9 Baα	9.3 Baα	8.3 Baα	11.6 (30) Aα	11.6 Aaα	12.3 Aaα	20.5 Aaα	12.7 Aaα	10.5 Abα
					Na/K					
Ap	0.21 (67) Aγ	0.22 Aaγ	0.16 Aaγ	0.21 Aaγ	0.17 (24) Aγ	0.18 Aaγ	0.14 Abγ	0.17 Aaγ	0.17 Aaβ	0.16 Aaγ
Btf1	0.49 (99) Aβ	0.62 Aaβ	0.38 Aaβ	0.41 Aaβ	0.22 5(2) Bβ	0.24 Baβ	0.22 Baβ	0.21 Baβ	0.17 Bbβ	0.27 Baβ
Btf2	1.45 (101) Aα	1.71 Aaα	1.08 Aaα	1.33 Aaα	0.46 (92) Bα	0.39 Baα	0.46 Baα	0.52 Baα	0.32 Bbα	0.60 Baα
					Ca/Mg					
Ap	3.47 (14) Bα	3.42 Baα	3.57 Baα	3.48 Baα	4.75 (35) Aα	4.61 Aaα	4.25 Aaα	5.14 Aaα	5.06 Aaα	4.43 Aaα
Btf1	2.58 (22) Aβ	2.44 Aaβ	2.72 Aaβ	2.65 Aaβ	2.60 (24) Aβ	2.64 Aaβ	2.50 Aaβ	2.60 Aaβ	2.52 Aaβ	2.67 Aaβ
Btf2	1.07 (28) Aγ	1.88Aabγ	1.71 Abγ	2.16 Aaγ	1.89 (27) Aγ	1.98 Aaγ	1.63 Aaγ	1.93 Aaγ	1.81 Aaγ	1.97 Aaγ

[1] Based on Alves (1997). [2] Numbers in parentheses represent coefficients of variation. [3] Capital letters compare sub-areas; small letters, distances to grapevines; and Greek letters, horizons.

Unlike the findings of Pereira & Cordeiro (1987) on Vertisols, concentrations of NH_4Cl -extractable cations were generally significantly greater in the vineyard than in the clearing, especially for points closer to the grapevines (Table 5). Considering the bulk density for each horizon as indicated in table 1, the increase in content of NH_4Cl-extractable cations to a depth of 0.9 m was about 5.8 mol m^{-2} of Na, 6.9 mol m^{-2} of K, 1.7 mol m^{-2} of Mg and 6.2 mol m^{-2} of Ca. The increases in Ca and Mg contents can be explained by considering the production inputs described above. In the case of K and especially Na, however, the inputs calculated from the information available fall short of the increase observed in the soil. The change in the Na content is more than ten times the amount apparently applied in the irrigation water. Part of this increase may also be derived from the groundwater table; according to Souto Maior (1996), saturation extracts from the Btf4 horizons of a profile in this vineyard contained more than 3 cmol L^{-1} of Na. For the observed change in Na content to have originated from the groundwater table, about 180 L m^{-2} of capillary rise must have occurred. On an annual basis this is about 60 L m^{-2} (60 mm) or more than twice that estimated for slightly lighter textured soils under mango production (Heck et al., 2001).

Salinity

Despite the spatial differences in moisture holding capacity at saturation (Santos et al., 2001), the EC of the 1:1 ($EC_{1:1}$) and the saturated paste (EC_e) extracts exhibited very strong correlations in both the Ap (r_s = 0.96***) and Btf2 (r_s = 0.95***) horizons. Results from both measures revealed a significantly higher degree of salinity in the vineyard than in the clearing (Tables 6 and 7). Such a change was not observed by Pereira & Cordeiro (1987) on the Vertisols they studied. Specifically, the area with $Ec_e > 1.5$ dS m^{-1} (point at which grape production begins to suffer, according to Maas, 1986) for the Ap horizon increased from 20 to 62%, for Btf2 from 13 to 33% and for both horizons from 10 to 28%. Considering the average EC_e of the Ap horizon within 1 m of the plants (Table 6), the relation of Maas (1986) suggests a potential decrease in grape production of more than 13%.

The decrease in EC (for both extracts) observed with depth in the vineyard, but not in the clearing, also reflects a preferential salinization of the Ap horizon. In contrast, the trend observed for points up to 5 m from the collector canal in the clearing, suggests an enhanced leaching of salts. Despite these differences, the correlation of $EC_{1:1}$ values in the Ap with those in the Btf1 and Btf2 were stronger in the vineyard (r_s = 0.75*** and 0.65*** respectively) than in the clearing (r_s = 0.65*** and 0.32*); the correlation between the two Btf horizons was also stronger in the vineyard (r_s = 0.90*** vs 0.59***). These results can be attributed directly to the application of chemical inputs, combined with an intensification of moisture flux through the soil profile with irrigation and drainage.

Values of EC_e were generally well correlated with the concentrations of cations (especially the bivalent) in the saturated paste extracts in the vineyard (r_s = 0.88*** and 0.90*** for Ca in the Ap and Btf2 respectively; 0.83*** and 0.96*** for Mg; 0.45*** and 0.76*** for Na; 0.71*** and 0.55*** for K) and clearing (r_s = 0.95*** and 0.92*** for Ca in the Ap and Btf2 respectively; 0.96*** and 0.95*** for Mg; 0.81*** and 0.79*** for Na; 0.93*** and 0.42** for K). Accordingly, all four cations exhibited significantly larger concentrations in the vineyard than in the clearing, as well as closer to the grapevines (Table 7). Furthermore, unlike the NH_4Cl-extractable cations, the concentration of all cations in the saturate paste extracts exhibited significantly lower values for the Ap horizons near the collector canals in the clearing. The lack of a similar difference in the vineyard can be attributed to relatively uniform fertigation and liming. As with the NH_4Cl-extractable cations, however, the greater EC and cations concentrations of the saturate paste extracts near the grapevines also suggest a preferential accumulation due to water extraction by the plant roots.

In general, no significant influence of the elevation of the impermeable layer or thickness of

Table 6. Average composition of 1:1 soil extracts, according to sub-area as well as distance to collector canals and plants

	Clearing				Vineyard					
Horizon	All	Distance to collector canals (m)			All	Distance to collector canals (m)			Distance to plant (m)	
		0-5	5-10	10-15		0-5	5-10	10-15	0-1	1-2
Electrical conductivity in H_2O, dS m^{-1}										
Ap	0.25 (75)[1] Bα	0.20 Bbγ	0.18 Bbα	0.32 Baα	0.92 (85) Aα	0.94 Aaα	1.00 Aaα	0.85 Aaα	1.28 Aaα	0.55 Abα
Btf1	0.28 (83) Bα[2]	0.29 Baβ	0.19 Baα	0.31 Baα	0.65 (80) Aβ	0.75 Aaβ	0.60Aaαβ	0.58 Aaβ	0.87 Aaβ	0.43 Abβ
Btf2	0.32 (100) Bα	0.37 Baα	0.17 Baα	0.33 Baα	0.57 (69) Aγ	0.59 Aaγ	0.54 Aaβ	0.56 Aaβ	0.75 Aaγ	0.39 Abβ
pH in H_2O										
Ap	5.10 (8) Bα	5.09 Baα	5.07 Baα	5.13 Baα	5.63 (11) Aα	5.63 Aaα	5.62 Aaα	5.63 Aaα	6.00 Aaα	5.26 Bbα
Btf1	4.47 (8) Bβ	4.51 Baβ	4.53 Baβ	4.40 Baβ	4.64 (12) Bβ	4.76 Baβ	4.64 Baβ	4.51 Baβ	4.90 Aaβ	4.38 Bbβ
Btf2	4.48 (7) Aβ	4.48 Aaβ	4.57 Aaβ	4.44 Aaβ	4.58 (12) Aβ	4.56 Aaγ	4.69 Aaβ	4.54 Aaβ	4.73 Aaγ	4.42 Aaβ
pH in 1 mol L^{-1} KCl										
Ap	4.20 (9) Bα	4.14 Baα	4.10 Baα	4.30 Baα	4.99 (16) Aα	5.01 Aaα	4.99 Aaα	4.98 Aaα	5.47 Aaα	4.52 Abα
Btf1	3.75 (6) Bβ	3.77 Baβ	3.78 Baβ	3.71 Baβ	3.92 (14) Bβ	4.06 Baβ	3.95 Baβ	3.78 Baβ	4.17 Aaβ	3.68 Cbβ
Btf2	3.73 (6) Bβ	3.74 Baβ	3.70 Baβ	3.73 Baβ	3.84 (10) Bβ	3.87 Baβ	3.80 Baβ	3.83 Baβ	3.96 Aaγ	3.72 Bbβ
Δ pH										
Ap	0.90 (9) Aα	0.95 Aaα	0.97 Aaα	0.82 Abα	0.64 (16) Bβ	0.62 Baβ	0.63 Baα	0.65 Baβ	0.53 Bbβ	0.74 Baα
Btf1	0.72 (6) Aβ	0.74 Aaβ	0.75 Aaβ	0.70 Aaβ	0.72 (14) Aα	0.70 Aaα	0.70 Aaα	0.74 Aaα	0.73 Aaα	0.70 Aaα
Btf2	0.74 (6) Aβ	0.74 Abβ	0.87Aaαβ	0.70Aabβ	0.74 (10) Aα	0.69Aaαβ	0.89 Baα	0.71Aaαβ	0.76 Aaα	0.71 Aaα

(1) Numbers in parentheses represent coefficients of variation. (2) Capital letters compare sub-areas; small letters, distances to grapevines; and Greek letters, horizons.

Table 7. Average composition of saturated paste extracts, according to sub-area as well as distance to collector canals and plants

Horizon	Clearing				Vineyard					
	All	Distance to collector canals (m)			All	Distance to collector canals (m)			Distance to plant (m)	
		0-5	5-10	10-15		0-5	5-10	10-15	0-1	1-2
Electrical conductivity, dS m^{-1}										
Ap	0.83 (76)(1) Bα	0.70 Bbα	0.57 Bbα	1.09 Baα	2.30 (59) Aα	2.57 Aaα	2.19 Aaα	2.07 Aaα	2.89 Aaα	1.70 Abα
Btf2	0.72 (108) Bβ	0.80 Baα	0.38 Baα	0.77 Baβ	1.21 (71) Aβ	1.27 Aaβ	1.13 Aaβ	1.19 Aaβ	1.56 Aaβ	0.85 Abβ
pH										
Ap	4.40 (14) Bα (2)	4.25 Baα	4.36 Baα	4.58 Baα	5.06 (22) Aα	4.88 Abα	5.21Aabα	5.18 Aaα	5.50 Aaα	4.63 Bbα
Btf2	3.99 (4) Aβ	4.03 Aaβ	3.92 Aaβ	3.98 Aaβ	4.04 (5) Aβ	4.06 Aaβ	3.95 Aaβ	4.05 Aaβ	4.07 Aaβ	4.00 Aaβ
Na, cmol$_c$ kg^{-1}										
Ap	0.57 (102) Bβ	0.60 Bbβ	0.38 Bbα	0.64 Baα	0.80 (40) Aα	0.89 Aaα	0.69 Aaα	0.78 Aaα	0.86 Aaα	0.74 Abα
Btf2	1.44 (143) Bα	1.68 Aaα	0.55 Aaα	1.54 Aaα	1.17 (139) Aα	1.45 Aaα	0.79 Aaα	1.07 Aaα	1.24 Aaα	1.09 Baα
K, cmol$_c$ kg^{-1}										
Ap	0.96 (72) Bα	0.72 Bbα	0.64 Bbα	1.36 Baα	5.23 (71) Aα	4.76 Aaα	6.42 Aaα	5.09 Aaα	6.58 Aaα	3.84 Abα
Btf2	0.22 (145) Bβ	0.26 Baβ	0.10 Baβ	0.21 Baβ	1.18 (119) Aβ	1.06 Aaβ	1.15 Aaβ	1.32 Aaβ	2.08 Aaβ	0.32 Abβ
Ca, cmol$_c$ kg^{-1}										
Ap	3.00 (75) Bα	2.45 Bbα	1.71 Bbα	4.20 Baα	12.58 (77) Aα	13.78Aaα	11.14Aaα	12.15Aaα	16.61Aaα	8.41 Abα
Btf2	1.96 (96) Bβ	2.00 Baα	1.09 Baβ	2.24 Baβ	4.32 (82) Aβ	4.74 Aaβ	3.29 Aaβ	4.41 Aaβ	5.70 Aaβ	2.93 Abβ
Mg, cmol$_c$ kg^{-1}										
Ap	1.49 (84) Bα	1.15 Bbα	1.01 Bbα	2.06 Baα	5.14 (72) Aα	6.15 Aaα	4.84 Aaα	4.32 Aaα	6.27 Aaα	4.05 Abα
Btf2	1.35 (92) Bα	1.43 Baα	0.83 Baα	1.46 Baα	3.33 (83) Aβ	3.30 Aaβ	3.30 Aaβ	3.39 Aaβ	4.50 Aaβ	2.17 Abβ
Na/K										
Ap	0.66 (57) Aβ	0.73 Aaβ	0.66Aabβ	0.60 Abβ	0.24 (69) Bβ	0.24 Baβ	0.14Bbβ	0.21Babβ	0.20 Baβ	0.28 Baβ
Btf2	9.75 (131) Aα	9.01 Aaα	7.30 Aaα	11.4Aaα	2.74 (134) Bα	3.26 Baα	2.60 Baα	2.37 Baα	1.48 Bbα	4.00 Baα
Ca/Mg										
Ap	2.23 (36) Bα	2.16 Aaα	2.09 Aaα	2.38 Baα	2.46 (33) Aα	2.38 Aaα	2.32 Aaα	2.68 Aaα	2.58 Aaα	2.34 Baα
Btf2	1.46 (18) Aβ	1.41 Abβ	1.30 Abβ	1.58 Aaβ	1.42 (26) Aβ	1.49 Aaβ	1.14 Abβ	1.43Aaβ	1.41 Aaβ	1.42 Aaβ
Sodium adsorption ratio, mmol$^{-0.5}$ L$^{0.5}$										
Ap	0.39 (62) Aβ	0.41 Aaβ	0.36 Aaβ	0.38 Aaβ	0.30 (36) Bβ	0.28 Aaβ	0.29 Aaβ	0.32 Aaβ	0.29 Baβ	0.31 Aaβ
Btf2	0.92 (96) Aα	1.02 Aaα	0.61 Aaα	0.93 Aaα	0.59 (98) Aα	0.70 Aaα	0.46 Aaα	0.53 Aaα	0.54 Abα	0.63Aaα

(1) Numbers in parentheses represent coefficients of variation. (2) Capital letters compare sub-areas; small letters, distances to grapevines; and Greek letters, horizons.

the pediment was encountered for the salinity of the water extracts. Similarly to the NH$_4$Cl-extracts, however, water soluble K in the Btf2 horizon of the vineyard exhibited the smallest values in the third quartile of pediment thickness. Lower EC and smaller concentrations of the bivalent cations were also generally encountered in the Ap horizon in the highest and lowest quartile of points in the clearing; in the vineyard, however, relative surface elevation did not exert any detectable influence on salinity. No significant relationship was observed between EC and landform, but elements of the vineyard with convex profile curvature were less leached of soluble bivalent cations; in contrast, the removal of soluble K appeared to be stronger in elements with convex plan curvature.

Ca/Mg ratios

As indicated in tables 5 and 7, the ratio of Ca/Mg in the NH_4Cl - and saturated paste extracts was higher in the Ap horizon and decreased with depth in both sub-areas. This pattern can be partially attributed to preferential uptake of Ca by plants. In the NH_4Cl extracts, as well as in the saturated paste extracts, the Ca/Mg ratios in the Ap horizon of the vineyard were usually significantly larger than in the clearing. These changes are most likely due to the addition of dolomitic lime and, to a lesser extent to the irrigation water and fertilizers, all of which contained more Ca than Mg.

Despite the localized addition of superphosphate at planting, no significant differences in Ca/Mg ratios were observed in the extracts as a function of distance from the grapevines (Tables 5 and 7). Point within 1 m of the grapevines did, however, exhibit significantly larger ratios for the Ap horizon than those in the clearing. Consequently, in both sub-areas, no significant correlations were observed between the Ap and Btf2 horizons for the two extracts. Moreover, no consistent influence of canal distance was evident in the vineyard, while in the clearing smaller ratios were encountered in the Btf2 horizon for points within 10 m.

No significant influence of pediment thickness was observed for the Ca/Mg ratios in either the NH_4Cl or saturated paste extracts. The elevation of the impermeable layer and soil surface also did not exert any detectable influence in the vineyard. In the clearing, however, larger ratios were found in saturated paste extracts of the Ap horizon at the points where the surface and impermeable layer elevations were lower (and vice versa). The same behavior was also observed in the NH_4Cl extracts in relation to elevation of the surface. Similarly, only the ratios in the Ap horizons exhibited differences related to surface profile curvature (Table 4).

Sodicity

The ratios of Na/K in both the NH_4Cl and saturated paste extracts were generally significantly smaller in the Ap than in the Btf horizons (Table 5 and 7). As with the Ca/Mg ratios, this behavior can be partially attributed to preferential cycling of K by plants. The smaller Na/K ratios observed in the vineyard, as well as closer to the grapevines, were most likely caused by the addition of K-bearing fertilizers. Fertilizer-induced decreases in the Na/K ratio have also been reported for irrigated Latosols (Pereira & Siqueira, 1979) and Vertisols (Pereira & Cordeiro, 1987) in the region. A lack of significant differences in Na/K ratios for the Ap horizon, between the two sub-areas, as well as in function of distance to the grapevines, likely reflects sodification from the irrigation and groundwater. The larger Na/K ratios observed in the saturate paste extracts in the Ap horizons closer to the collector canals could be attributed to the deposition of more sodium rich sub-surface material during canal construction (Santos et al., 2001) and a subsequent retardation of moisture infiltration.

Sodium adsorption ratios of the saturate paste extracts behaved similarly to Na/K in relation to profile depth and distance to grapevines, but showed no influence of distance to collector canals (Table 7). Furthermore, only the Ap horizon exhibited significantly smaller SAR in the vineyard than in the clearing. Though the values in the Ap horizon were less variable in the vineyard, the correlation between this horizon and the Btf2 were weaker in the vineyard ($r_s = 0.30^*$ vs $r_s = 0.61^{**}$ in the clearing). These results reflect the lower solubility and mobility of the Ca and Mg applied as superphosphate and dolomitic lime, as compared with the fertilizer K. None of the points examined were considered sodic (SAR > 13).

Neither the Na/K ratios nor the SAR were significantly influenced by the elevation of the impermeable layer in either sub-area. Pediment thickness also exerted no apparent influence in the clearing, but in the vineyard the Na/K ratios were significantly smaller in the quartile of points with next-to-thinnest pedimentary cover. In contrast, the influence of surface elevation was evident only in the clearing, where larger SAR and Na/K were found in the Ap horizons at lower points. Only the Btf2 horizons in the vineyard exhibited significant differences in both Na/K and SAR, due to landform (Table 4): larger values were found in elements with concave compared with convex profile curvature.

Acidity

As indicated by the pH measured in the water ($pH_{1;1}$, pH_e) and 1 mol L^{-1} KCl (pH_{KCl}) extracts, the Ap horizons were less acid and contained less exchangeable acidity (smaller ΔpH) in the vineyard than in the clearing; no such significant differences occurred in the Btf horizons (Table 6 and 7). Consequently, the amount of exchangeable acidity in the vineyard was also significantly less in the Ap than the Btf horizons. These changes can be attributed directly to the application of lime. In contrast, the Vertisols studied by Pereira & Cordeiro (1987) were not limed and experienced an increase in acidity with the application of urea and ammonium fertilizers.

Like EC, the correlation between soil acidity in the Ap and the two Btf horizons was generally stronger in the vineyard ($r_s = 0.63^*$ and $0.25^{p\,=\,0.06}$ for pH_{KCl} in the Btf1 and Btf2; 0.54*** and 0.25** for $pH_{1:1}$; 0.42** and 0.42** for ΔpH) than in the clearing ($r_s = 0.34^*$ and 0.14 for pH_{KCl} in the Btf1 and Btf2; 0.32* and 0.04 for $pH_{1:1}$; 0.48** and 0.33* for DpH). The variability of these indicators of soil acidity was, however, greater in the vineyard (Tables 6 and 7). Both of these tendencies can be attributed to localized lime applications; indeed, larger pH and smaller ΔpH were observed closer to the grapevines. Soil acidity was not noticeably influenced by distance to the collector canals.

Pediment thickness and depth to the impermeable layer did exert limited influence on acidity, but only the pH_{KCl} of the Btf1 horizon in the clearing exhibited significantly lower values where the pediment was thinner. The acidity of the Ap horizon in the clearing was also related to surface elevation: significantly higher pH was observed at higher elevations and lower ΔpH was observed in the intermediate elevations. In the vineyard, only the pH_{KCl} was influenced by surface elevation, with the lowest values being observed the next-to-lowest quartile of points. Though more frequent in the vineyard, the influence of landform on acidity was also limited (Table 4): elements with convex profile curvature and those with concave plan curvature were less acid.

CONCLUSIONS

1. Three years of irrigated grape production decreased soil acidity, but also caused slight increases in sodicity and significant increases in the degree of salinity; these changes were generally greater near the grapevines.

2. While the increase in the proportion of Ca and K could be associated with production inputs, the increase in Na was attributed to capillary rise from the saline groundwater table.

3. Preferential leaching of the Ap horizon near the collector canals was evident in the clearing, but not in the vineyard.

4. Though pediment thickness exerted minimal effect on the salinity of these soils, surface and impermeable layer elevation as well as surface curvature influenced variability.

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