VITICULTURAL TERROIRS IN STELLENBOSCH, SOUTH AFRICA. I. THE IDENTIFICATION OF NATURAL TERROIR UNITS

Victoria A CAREY[1]*, D. SAAYMAN[2], E. ARCHER[1], G. BARBEAU[3] and M. WALLACE[4]

1: Department of Viticulture and Oenology, Stellenbosch University, Private Bag X1, 7602 Matieland, South Africa
2: Distell, P.O. Box 184, 7599 Stellenbosch, South Africa
3: Unité Vigne et Vin, Centre INRA d'Angers, 42 rue G. Morel, BP 57, 49071 Beaucouzé, France
4: Department of Agriculture, Private Bag X1, 7607 Elsenburg, South Africa

Abstract

Aims: A natural terroir unit (NTU) can be defined as a unit of land that is characterized by relatively homogenous topography, climate, geological substrate and soil. The mapping of NTUs is the first stage of data acquisition in a terroir study. This study aimed to identify NTUs using a Geographic Information System and to characterize the Stellenbosch Wine of Origin District using existing digital information at the scale of a wine producing district.

Methods and results: The study area is bordered by mountains, situated close to the Atlantic Ocean and bisected by the Eerste river valley, resulting in notable spatial variation of all climatic parameters. The geology is complex due to the high degree of tectonic movement and mixing of parent material. Terrain morphological units, altitude, aspect and soil type were used as primary keys/variables for the identification of NTUs. Each of the identified units was further described with respect to the extent of the expected sea breeze effect and, for certain of the soil types, the associated parent material. A total of 1389 NTUs were identified in the Stellenbosch Wine of Origin District.

Conclusions: Many of the natural terroir units identified for the Stellenbosch Wine of Origin District are of a size that is not economically or practically viable.

Significance and impact of the study: The natural terroir units should be grouped into larger, more manageable and thus more viable terroir units using data relating their viticultural and oenological potential. This task will be addressed in subsequent companion papers.

Key-words: geographic information system, grapevine, natural terroir unit, Stellenbosch, South Africa

Résumé

Objectif : Une unité de terroir naturel (NTU) peut-être définie comme une unité de surface caractérisée par une topographie, un climat, un sol et un substrat géologique relativement homogènes. La cartographie des NTU est la première étape de l'acquisition de données dans une étude de terroir. Cette étude a pour objectifs d'identifier les UTN en utilisant un Système d'Information Géographique et de caractériser le district des vins d'origine de Stellenbosch en utilisant des informations numériques existantes à l'échelle d'un district viticole.

Méthode et résultats : Le domaine d'étude est bordé de montagnes, situé près de l'océan Atlantique et découpé par la vallée de la rivière Eerste offrant une variation spatiale notable de tous les paramètres climatiques. La géologie est complexe en raison de mouvements tectoniques de grande intensité et d'un mélange de la roche-mère. Les unités morphologiques de terrain, l'altitude, l'exposition et le type de sol ont été utilisés en premier lieu comme variables clés pour l'identification des UTN. Chacune des unités identifiées a ensuite été décrite en fonction de l'extension de l'effet des brises de mer prévu, et, pour certains types de sol, de la roche-mère associée. Un total de 1389 UTN a été identifié dans le district des vins d'origine de Stellenbosch.

Conclusion : Parmi les unités de terroir naturel identifiées pour le district des vins d'origine de Stellenbosch, nombreuses sont celles qui sont d'une taille économique et pratique non viable.

Signification et impact de l'étude : Les unités de terroir naturel devraient être regroupées en unités de terroir plus larges, plus faciles à gérer et plus viables en utilisant des données faisant référence au potentiel viti-vinicole. Ce travail sera adressé dans des articles subséquents.

Mots-clés : système d'information géographique, vigne, unité de terroir naturel, Stellenbosch, Afrique du Sud

manuscript received27 August 2008 - revised manuscript received5 September 2008

J. Int. Sci. Vigne Vin, 2008, **42**, n°4, 169-183

*Corresponding author: vac@sun.ac.za

INTRODUCTION

Natural terroir units have been defined by Laville (1993) as « a volume of the earth's biosphere that is characterized by a stable group of values relating to the topography, climate, substrate and soil ». Morlat (1989) provided a similar definition when he described the concept of the basic terroir unit (unité terroir de base). The grouping of such units in relation to the characteristics of the agricultural raw or transformed product obtained constitutes a terroir, i.e. the terroir cannot be defined in isolation from its product. Because the concept of the terroir relies on the intrinsic agronomic potential of the environment and is thus inseparable from the characteristics and « identity » of the final agricultural product, all studies to delimit terroirs should include two stages of data acquisition; firstly the mapping of pertinent environmental features in order to obtain relatively homogenous environmental units or natural terroir units and secondly, a study of the reaction of the crop to the environmental attributes of the delimited units (Morlat 1996).

The interaction of the grapevine with its immediate environment has long been a research focus in South Africa (Buys, 1971; Le Roux, 1974; Saayman, 1976; Saayman, 1977; Saayman and Kleynhans, 1978). The planting of cultivars directed towards quality wine production in the late 1980s has led to an increased focus on the implications of terroir for viticultural management and wine style and quality. This provided an impetus that lead to the initiation of a research program in this direction.

The high degree of topographic variation in the Stellenbosch Wine of Origin District and its proximity to the ocean together provide many diverse environments for viticulture, making this region a complex study area. The Stellenbosch Wine of Origin District is characterized by a combination of plains with straight slopes and low relief, undulating plains with moderate relief and free standing and undulating hills with high relief (Schultz 1997), resulting in a complex landscape. Topography is a static feature of the landscape and is described by altitude as well as the rate of change of altitude over distance and has thus components of slope form, slope inclination, slope aspect, altitude and relief (Schultz, 1997). Topography of this region is determined to a large extent by the geological formations present, with their inherent resistance to weathering being amongst the factors that shape the landscape (Wooldridge, 2000; Wooldridge, 2003). The Stellenbosch Wine of Origin District has an underlying layer of sedimentary formations of the Malmesbury group, which were deposited during the Precambrian Era (Theron *et al*., 1992). These underwent subsequent compaction and indurations. Tectonic movements during this period resulted in a north-west trending mountain chain. Intrusion of the Cape Granite Suite accompanied this folding. Two granitic plutons, with a coarse-grained texture, are present within the Stellenbosch Wine of Origin District. At the contact with the granite, the rocks of the Malmesbury Group were baked. The greywacke of the Stellenbosch-Somerset West area is representative of the contact metamorphic effect of the Cape granite intrusion. Subsequent erosion and deposition of the Cape Super Group sediments was followed by a period of orogeny during the Permian Period with consequent folding, uplifting and fracturing of formations. Sandstones and shales eroded, leaving remnants such as Simonsberg. Quaternary sediments and soils are also present throughout this region (Theron *et al*., 1992). Topography also determines the local climate either directly as a result of the change in the incidence of the sun's rays on the earth's surface or indirectly as a result of altered soil drainage patterns, exposure to wind and ventilation (Crowe, 1971). The elevation of the study area ranges from 5 m on the coastal plain to higher than 1,500 m above sea level in the Hottentots Holland Mountains. The rapid changes in elevation result in varying slope aspects. In this study area, the Simonsberg, Stellenboschberg and Jonkershoekberg are similarly oriented, resulting in predominantly south west or north east facing slopes, the Helderberg on the other hand results in dominant north west or south east facing slopes. The Bottelaryberg hills provide a variety of expositions. Climate is one of the dominant soil forming factors (De Blij, 1983) and there exists thus an inherent relationship between soil and topography (Wysocki *et al*., 2000). This is represented in the concept of a « catena », « a sequence of soils of similar age, derived from similar parent material, and occurring under similar macroclimatic conditions, but having different characteristics due to variation in relief and drainage » (Soil Classification Working Group 1991). Variation in drainage characteristics of the landscape can be defined with the aid of terrain morphology, with each terrain morphological unit (crest, scarp, midslope, footslope, valley bottom) having associated slope inclinations and slope shape (Kruger, 1973).

This paper describes the first step of a study to identify viticultural terroirs in the Stellenbosch Wine of Origin District in South Africa. Its aims are firstly to characterize the study area using existing digital environmental data and, secondly to identify natural terroir units using the spatial data and a geographic information system protocol. This was expanded from an initial study on a smaller study area, which included the slopes of the Bottelaryberg, Simonsberg and Helderberg in Stellenbosch (Carey, 2001).

DATA AND METHODS

Study area

The study area encompasses the Stellenbosch Wine of Origin District situated at 34 °S latitude and 19 °E longitude (figure 1). It covers an area of 84,537 ha, including non-arable land. The Stellenbosch wine producing region (statistics include those of Durbanville and Constantia) contains ca. 16 582 ha of vineyards, representing ca. 16 % of the country's vineyards, with the predominant cultivars being Cabernet Sauvignon (20 % of the total hectares planted), Chenin blanc (16 %), Sauvignon blanc (12 %), Merlot (11 %) and Shiraz (11 %) (SAWIS, 2002). The Stellenbosch Wine of Origin District includes the south-western flanks of the Simonsberg (1,390 m), the Jonkershoekberg (914 m), the Stellenboschberg (1,167 m) and the Helderberg (1,137 m), the western flanks of the Hottentots Holland mountains (1,598 m), the Bottelaryberg hills (477 m), the Eerste River valley and the coastal plain.

Climate

A network of automatic weather stations has been established in the Stellenbosch Wine of Origin District since 1994 (figure 2, table I). These weather stations represent various positions in the landscape. The parameters of temperature, relative humidity, rainfall, radiation, sun duration, wind speed and wind direction were averaged or summed, depending on whether or not the parameter is cumulative in nature, for the period of an hour. The temperature sensors are housed in a Stevenson screen 1.2 m above ground level. Data generated by this network for the period 1995 to 2002 was used to determine selected climatic variables and indices, namely the mean maximum temperature, minimum relative humidity, and number of hours with a wind speed greater than 4 m.s^{-1} during February, thermal-time index of Amerine and Winkler (1944) (adapted for the South Western Cape by Le Roux, 1974), Heliothermic index of Huglin (Huglin, 1993) and the mean February temperature index (De Villiers *et al.*, 1996). For the statistical analysis of climatic data, automatic weather stations were used as plots and years were used as replicates.

Digital topographic data

A land type reconnaissance survey (Land Type Survey Staff 1972-1999) was conducted by the Soils and

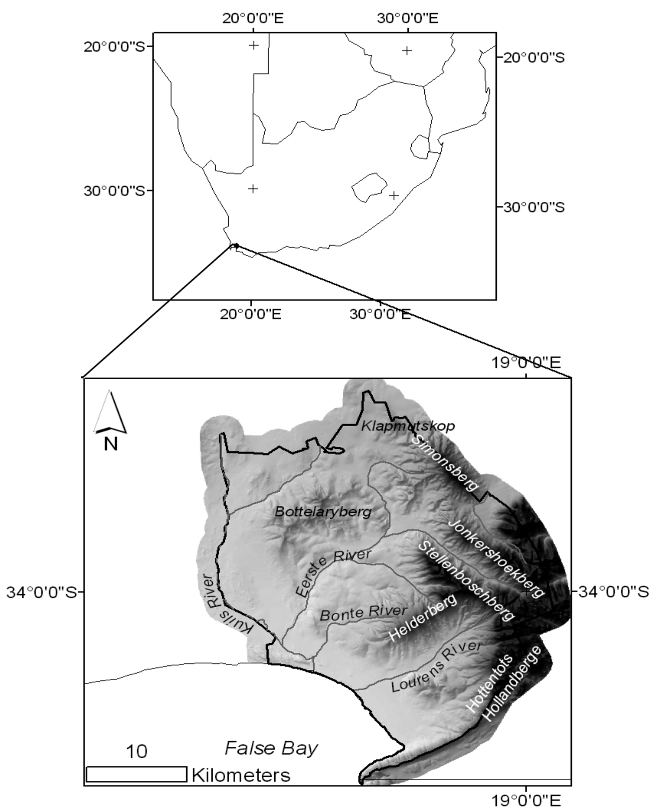

Figure 1 - The geographical position and boundaries (solid black line) of the Stellenbosch Wine of Origin District

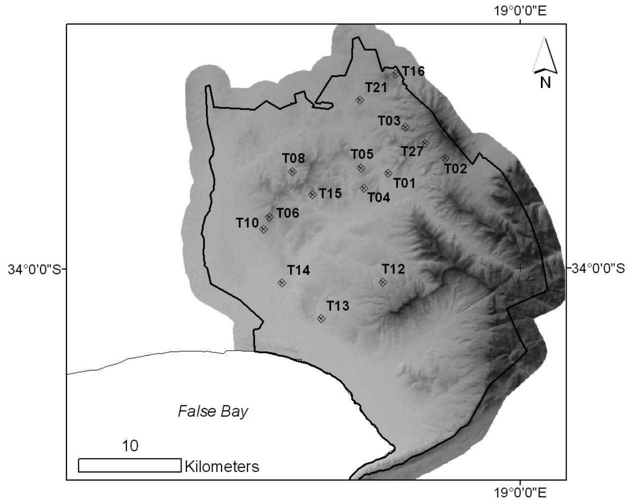

Figure 2 - Automatic weather station network in the Stellenbosch Wine of Origin District.

Irrigation Research Institute (now known as Agricultural Research Council Institute for Soils, Climate and Water or ARC ISCW). A Land Type refers to « a class of land over which the macroclimate, the terrain form and the soil pattern each displays a marked degree of uniformity » (MacVicar *et al.*, 1974) and during the survey; areas of relatively homogenous climate, topography and soil catenas were grouped into mapped units called Land Types. Each Land Type was described in an accompanying memoir in terms of the estimated chemical and physical properties for the pertinent soil series. Only the Land Type boundaries were mapped (1:250 000) but information provided within the memoirs makes it possible to narrow the soil chemical and physical description and mapped unit down to the terrain morphological unit level per Land Type. Slope profiles can be divided into segments based on slope shape and gradient (Wysocki *et al.*, 2000). Within the South African land-type system, five terrain morphological units are recognized, namely crest, scarp, midslope, footslope and bottomland (or valley bottom) (Kruger, 1973; MacVicar *et al.*, 1974). Whilst the Land Type terrain morphological units have not previously been mapped the memoirs state the percentage that each terrain morphological unit represents in a Land Type. These extents were estimated by the compilers from 1:50 000 topocadastral map sheets. In order to map terrain morphological units, a computer algorithm was developed in the AVENUE® language to extract the individual terrain units from a DEM based on user-entered physical parameters. Thus, from a DEM showing the topography of an area, the model will extract zones and classify them as valley bottom, footslope, midslope or crest (scarps are ignored as they have no agricultural potential). The algorithm makes extensive use of the hydrological functionality native to ArcView® 3.X. (ESRI 2000), and operates in the raster or « cell-based » GIS environment. For this study, a 50 m Digital Elevation Model (DEM) was used. The « DEMfill » command was used to « fill » all sinks, i.e. areas of internal drainage, contained within it to prevent spurious results later in the process. A dialog box was then used to estimate, according to the Land Type descriptions of the region, the required ratio of pertinent terrain units (for this study, crest = 12 %, midslope = 34 %; footslope = 41 % and valley bottom = 13 %). A seeding value was

Table I - Topographic and climatic data for automatic weather stations in the Stellenbosch Wine of Origin District. Values are means for the period 1995-2002.

Site (weather station)	Altitude	Aspect	Thermal Time Index[1]	Huglin Index[2]	Rain (Dec-Feb) mm	Mean Feb Temp °C	Max Feb Temp °C	Min RH Feb %	No hrs wind >4m.s-1 (Feb) hours
T01	148	SW	1897 ^{cd}	2322 ^{bc}	74.7 ^{bc}	22.1 ^{bcde}	28.4 ^{c}	43.9 ^{b}	204 ^{f}
T02	413	SSE	1700 ^{a}	2129 ^{a}	97.0 ^{d}	21.3 ^{abcd}	27.7 ^{ab}	55.6 ^{e}	18 ^{ab}
T03	342	NW	1742 ^{ab}		66.3 ^{abc}	22.0 ^{abcde}	29.2 ^{d}	52.6 ^{de}	5 ^{a}
T04	148	NW	1955 ^{def}	2422 ^{ef}	71.1 ^{bc}	22.3 ^{cde}	29.9 ^{e}	51.3 ^{de}	11 ^{ab}
T05	210	WNW	1878 ^{c}	2336 ^{bc}	66.4 ^{abc}	22.0 ^{abcde}	29.1 ^{d}	54.1 ^{de}	81 ^{cd}
T06	250	ESE	1750 ^{ab}	2165 ^{a}	67.7 ^{abc}	21.2 ^{ab}	27.7 ^{a}	50.1 ^{cde}	85 ^{d}
T08	235	N	1800 ^{b}	2159 ^{a}	75.7 ^{bc}	21.2 ^{abc}	27.1 ^{a}	51.9 ^{de}	253 ^{g}
T10	130	SW	1750 ^{ab}	2146 ^{a}	52.3 ^{a}	21.0 ^{a}	27.1 ^{a}	51.6 ^{de}	197 ^{f}
T12	225	NNW	2001 ^{f}	2415 ^{de}	98.0 ^{d}	22.7 ^{e}	29.5 ^{de}	52.3 ^{de}	46 ^{bc}
T13	56	WSW	1952 ^{def}	2340 ^{bcd}	75.9 ^{bc}	22.2 ^{bcde}	28.4 ^{c}	54.3 ^{de}	250 ^{g}
T14	27	S	1986 ^{ef}	2360 ^{cde}	63.4 ^{ab}	22.2 ^{bcde}	28.4 ^{c}	51.0 ^{de}	115 ^{de}
T15	153	S	1928 ^{cde}	2277 ^{b}	74.1 ^{bc}	22.2 ^{bcde}	28.4 ^{c}	52.0 ^{de}	137 ^{e}
T16	260	NE	1981 ^{ef}	2329 ^{bc}	82.9 ^{cd}	22.7 ^{e}	28.3 ^{bc}	52.7 ^{d}	206 ^{f}
T21	177	NW	1997 ^{f}	2499 ^{f}	57.0 ^{ab}	22.4 ^{de}	30.0 ^{e}	45.7 ^{bc}	143 ^{e}
T25	92	NNW	2073 ^{g}	2900 ^{g}	62.8 ^{ab}	21.4 ^{abcd}	30.6 ^{f}	33.6 ^{a}	
T26	320	WNW	1954 ^{cdef}	2298 ^{bc}	60.5 ^{abc}				
T27	320	SW	1677 ^{a}		76.6 ^{bc}				
p-value (site)			$\leq$0.0001	$\leq$0.0001	$\leq$0.0001	0.02	$\leq$0.0001	$\leq$0.0001	$\leq$0.0001
p-value (vintage)			$\leq$0.0001	$\leq$0.0001	$\leq$0.0001	$\leq$0.0001	$\leq$0.0001	$\leq$0.0001	0.0001

[1]Thermal-time index of Amerine & Winkler (1944) (adapted for the South Western Cape by Le Roux, 1974)
[2]Huglin, 1983

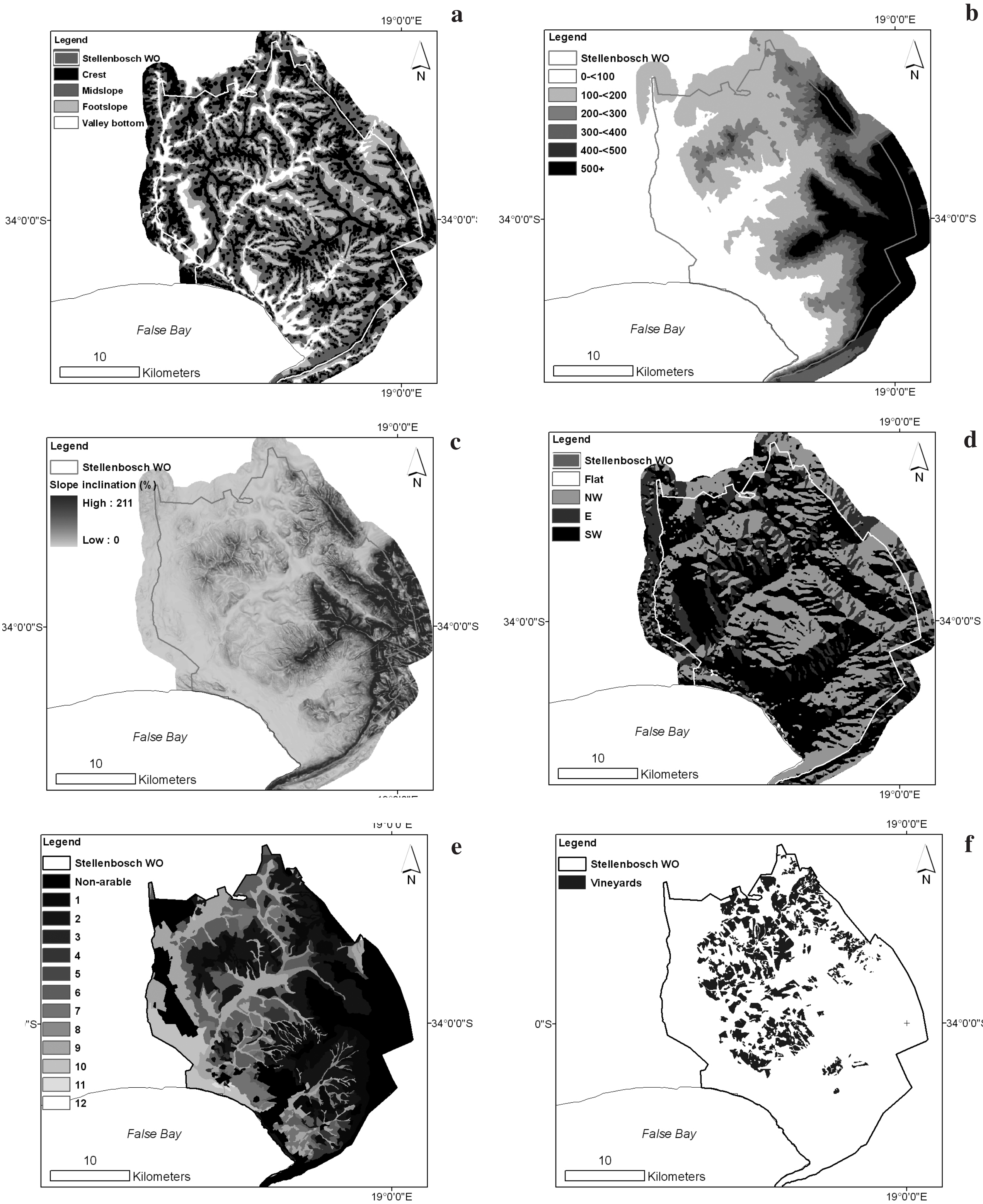

Figure 3 - Spatial topographic, soil and vineyard data for the Stellenbosch Wine of Origin District. (a) Terrain Morphological units. (b) Altitude (m). (c) Slope inclination (%)(d) Aspect. (e) Soil associations (read in conjunction with table II) (Adapted from Ellis and Schloms, 1975; Ellis *et al.*, 1976; Ellis *et al.*, 1980) (f) Estimated surface planted to vineyards in 2001 (ARC Institute for Soil, Climate and Water).

entered, based on the resolution of the DEM (for this study, 500), to determine the stream catchment size. The ESRI functions « Flow Direction » and « Flow Accumulation » were run on the DEM. This allocated and tallied all upstream cells on a cumulative basis based on their flow direction. Those with the highest values were considered to be potential streams. This information was used to define a stream network, i.e valley bottom network. Similarly those cells with very low values were defined as ridges and a ridge, i.e. crest, network was defined. Slope was calculated using basic GIS functionality. « Cost Distance » analysis, with the cost being the steepness of the slope, was used to calculate the least cost travel from stream to ridges. This accounted for undulations and curvature of the facet leading to the ridge. Likewise the cost path was calculated from ridge to stream. A Euclidean distance was calculated along these cost path cells. The ratios apportioned to midslope or footslope were then calculated according to the slider settings previously selected (namely, 0.13, 0.40 and 0.75). Areas adjacent to the stream network and with slopes less than 3 % in slope were allocated to valley bottoms. A new grid was created showing the terrain units (figure 3a).

A 50 m Digital Elevation Model (DEM) was used to determine the elevation, aspect and slope inclination using Spatial Analyst™ in ESRI®ArcMap™ 8.2. Temperature generally decreases with increasing altitude in the tropospheric layer. This temperature lapse rate varies with region and season (Schultz 1997), but can be accepted as being approximately 0.3 °C for every 100 m above sea level for South Africa (Le Roux, 1974). The effects of small differences in altitude are not known and most of the world's great table wines come from altitudes lower

Table II - Predominant soil associations found in the Stellenbosch Wine of Origin District.

Soil association	% of area	Soil forms[1]	Viticultural potential[2]	Soil class
A. Shallow (<0.5 m) residual soils on hard or weathering rock	11.1	Mispah, Glenrosa, Cartref	These shallow soils have a low potential for growth vigor due to the limited area available for root growth and low soil water holding capacity.	1
Av. Very shallow complex of A	0.04			
B. Red and yellow freely drained structureless or weakly structured soils	17.3	Hutton, Clovelly, Avalon, Bainsvlei, Pinedene, Vilafontes	At similar texture and depth, these soils stimulate similar (and strong) growth vigor in grapevines. Good soil water holding capacity.	2
Bv. Shallow (<0.5 m) complex of B	0.2			
Bs. Stony complex of B	3.7			3
C. Dry duplex soils (Duplex refers to a clear textural change from topsoil to subsoil. The topsoil is sandy while the subsoil has a high clay content)	3.2	Swartland, Sterkspruit, Estcourt, Klapmuts, Sepane, Valsrivier	These soils are generally residual in nature and, although shallow react well, to deep soil preparation. Good soil water holding capacity.	4
Cs. Stony complex of C	0.0			5
D. Medium deep (0.5 m-1.0 m) wet duplex soils	12.4	Kroonstad, Longlands, Wasbank	Wetness can limit root growth in the early season, which may lead to water stress in the late summer due to insufficient root development and low soil water holding capacity.	6
Dv. Shallow (<0.5 m) complex of D	6.2			7
E. Well-drained deep (>1.0 m) alluvial sands	2.2	Dundee, Oakleaf, Fernwood (dark)	These sandy soils have a low water holding capacity	8
F. Poorly drained alluvial soils	7.2	Westleigh, Fernwood, Dundee, Katspruit, Wasbank, Champagne	These soils are not suitable for quality viticulture	9
G. Saline duplex and alluvial loam soils	7.3	Estcourt, Valsrivier, Klapmuts, Swartland, Sepane		
H. Deep (>1.0 m) dry sands on rock or calcrete	4.2	Fernwood (bleached)	These sandy soils have a low water holding capacity	10
Hv. Shallow (<0.5 m) complex of H	4.2			11
J. Wet plinthic soils	0.01	Avalon, Westleigh, Bainsvlei, Tukulu, Pinedene	These soils have a fluctuating water table, which may be positive under dry land conditions	12

[1]Soil Classification Working Group (1977, 1991)
[2] Van Zyl & Van Huyssteen (1979)

than 500 m (Gladstones, 1992). Altitude was therefore divided into 100 m increments up to an altitude of 500 m. A sixth category grouped altitudes higher than this level (figure 3b). Slope inclination in the Stellebosch Wine of Origin District varies between 0 % and greater than 95 %. Slope inclination affects sunlight interception and drainage of air and water. Slope inclination (figure 3c) was, however, not included as an independent variable in the definition of natural terroir units as it is implied, together with slope form, within the definition of terrain morphological units (Kruger, 1973). Aspect categories were selected in order to represent the slope interception of sunlight and dominant winds and were divided into east (45 ° to 135 °), south-west (135 ° to 270 °) and north-west (270 ° to 45 °, passing through 0 °) (figure 3d). East facing slopes warm earlier in the morning and cool earlier in the afternoon (Carey, 2001). South-westerly slopes are cooler due to interception of the sea breeze in the early afternoon (Bonnardot, 199 ; Bonnardot, 1999 ; Carey, 2001 ; Bonnardot *et al.*, 2002) and reduced interception of sunlight (Wooldridge and Beukes, 2003). North-westerly slopes are warmest due to being protected to a certain extent from the moderating influence of the sea (Bonnardot, 1997; Bonnardot, 1999; Carey, 2001) and receiving the most direct radiation in the Southern Hemisphere (Schultz, 1997).

Digital soil data

The available soil data was that of soil associations where soil forms (Soil Classification Working Group, 1977) were grouped based on depth, stoniness and general pedogenetic characteristics. Soil forms are expected to have a similar set of genetic processes regardless of parent

Table III - Classes and codes (bold type) for environmental variables used for the determination of natural terroir units in the Stellenbosch Wine of Origin District. Non-arable land, e.g. urban areas, marshlands, water, steep stony slopes, rock and stony outcrops, was excluded from the determination of natural terroir units

Environmental variable[1]				
Terrain unit	**Aspect (°)**	**Altitude (m)**	**Soil**	**Geology**
Crest **(c)**	Flat **FLAT**	≤100 **(1)**	Residual soils (shallow soils on hard or weathering rock) **(A)**	**Alluvium**
Scarp **(sc)**	0-45, 270-360 **(NW)**	>100; ≤200 **(2)**	Freely drained structureless soils **(B)**	**Silcrete**
Midslope **(m)**	45-135 **(E)**	>200; ≤300 **(3)**	Stony, freely drained structureless soils **(Bs)**	**Ferricrete**
Footslope **(f)**	135-270 **(SW)**	>300; ≤400 **(4)**	Dry duplex soils **(C)**	River **terrace** gravel
Valley bottom **(v)**	-	>400; ≤500 **(5)**	Stony complex of shallow residual and dry duplex soils **(Cs)**	**Scree**/talus/ alluvium grading into piedmont gravel or gritty sand
-	-	Alt>500 **(6)**	Medium deep wet duplex soils **(D)**	Quartzite, conglomerate and slate of the **Franschhoek formation**
-	-	-	Shallow wet duplex soils **(Dv)**	Shale, greywacke, quartzite and minor volcanic rocks of the **Tygerberg formation**
-	-	-	Well-drained deep alluvial soils **(E)**	Conglomerate, sandstone and minor shale of the **Magrug formation**
-	-	-	Poorly-drained alluvial and saline duplex and alluvial loam soils **(F+G)**	**Aeolian sands**
-	-	-	Excessively drained deep sandy soils **(H)**	**Brackish calcareous soil**
-	-	-	Shallow dry sands on rock or calcrete **(Hv)**	Weathering products of granite (gravelly clay) **(Qg)**
-	-	-	Red or yellow structureless soils with a plinthic horizon **(J)**	Weathering products of Malmesbury rocks (loam and sandy loam) **(Qgg)**
-	-	-	-	**Granite**
-	-	-	-	**Sandstone**

[1]These variables have no horizontal relationship

material or mineral composition (Wooldridge, 1988). Soil associations represent a grouping of soil forms for which a similar response is expected. These soil associations are generalized and do not contain all the information that would be available at the level of a soil form. A digital soil map compiled from a Peri-Urban Soil Survey mapped on a scale of 1:25 000 and 1:50 000 by Ellis and Schloms (1975) and Ellis *et al.* (1976) respectively, was obtained. A digital map of soil associations of the Western Cape mapped on a scale of 1:250 000 by Ellis *et al*. (1980) was used to complete the data in mountainous areas of the study area. Sixteen soil associations, excluding areas classified as urban or marshland, were found in the Stellenbosch Wine of Origin District. Some of these associations may be found together with other soil types. These associations were grouped to provide 12 classes (table II and figure 3e). All urban areas, marshland, water, steep stony slopes and rock or stony outcrops were grouped together as unsuitable for viticulture (table III). These are labeled as class « 0 » (table III) and are excluded from the determination of natural terroir units.

Digital geological data

Geological parent material may affect the colour, texture and/or mineral composition of resulting soils. Sandstones are generally poorly supplied with plant mineral nutrients (Van Schoor, 2001). Soils from granite can be expected to contain coarser fragments, soils from Malmesbury rocks to be more abundant in clay, silt and fine sand and Table Mountain sandstone to result in more sand-sized particles (Van Schoor, 2001). Soil mineral composition affects the total potassium (K) content of soils, the K supplying power of soils and the ability of the soil to buffer K (Wooldridge, 1988). Plants grown on soils with a low K buffering capability may be subject to excessive K consumption (Wooldridge, 1988). Granitic soils generally have the highest potassium content (Wooldridge, 1988 ; Van Schoor, 2001), which is not well buffered, favoring rapid plant uptake (Wooldridge, 1988). This will, however, depend also on the soil water availability and the colonization of the soil profile by roots and the functioning of the system. It is, however, particularly difficult to associate geology with derived soils in the Stellenbosch wine producing area due to the high degree of tectonic movement and mixing of parent material. *In situ* weathering of rocks is seldom the only source of soil formation and mixing of parent material can be considered significant (Van Schoor, 2001). The material from which the soil has developed often has a very different geological origin to that of the underlying « parent » material. Transported granitic soils can overlie Malmesbury bedrock (Theron *et al*., 1992). Geology was therefore only considered to be of importance for residual soils, dry duplex soils and freely drained structureless soils, although even this last mentioned may consist of mixed parent material (Conradie *et al*., 2002).

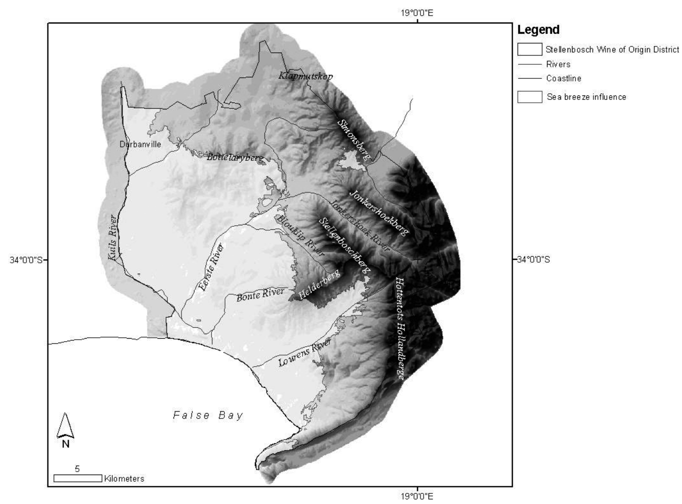

Figure 4 - Extent of the sea breeze effect in the Stellenbosch Wine of Origin District estimated from modeled relative humidity values (RAMS generated) on a grid of 1 km at 15:00 SAST (adapted from Bonnardot and Cautenet, 2008)

Digital geological data compiled from a 1:250 000 geological map of the Council for Geoscience (Theron, 1990), was the best available data for the study area. This scale is not suited to a terroir study at the level of a district. It has, therefore, not been used as a primary classifier but rather as an additional descriptor. The classification of the geological formations used in the identification of NTUs is shown in table III. Due to their similar texture, the granite of the two plutons was placed in one class (Class: Granite). Scree, talus and alluvium that grades into piedmont gravel, were grouped with gritty sand, into which they grade on the mountain slopes (Class: Scree). The aeolian sands of the Springfonteyn, Witzand and Langebaan formations (Theron *et al*., 1992) were placed in the same class (Class: Aeolian sands). The other classes are self-explanatory from table III.

Extent of the sea breeze effect

The extent of the sea breeze is complex to determine. As the sea breeze penetrates overland, thermal convection from the land results in a blending of moist sea air and dry air from the land and therefore instability of the sea breeze. This results in dry air being included in the humid maritime air (Carrega, 1995) at the contact between maritime and continental air.

A grid of relative humidity values at a resolution of 1 km at 15:00 South African Standard Time for the Stellenbosch region was obtained from LaMP CNRS and ARC ISCW (Bonnardot and Cautenet, 2008). This grid was created with the aid of the Regional Atmospheric

Modeling System (RAMS 4.3) (Pielke *et al.*, 1992; Cotton *et al.*, 2003), together with the RAMS/HYPACT Evaluation and Visualization Utilities (REVU). RAMS uses a system of nested grids to provide high spatial resolution for smaller areas within a larger domain, which has been modeled at a lower resolution. Three nested grids, 5 km, 1 km and 200 m have been used within the South Western Cape (Bonnardot and Cautenet, 2008). These grids were situated within the computational domain of the coarse parent grid with a resolution of 25 km. RAMS was initialized with upper-atmospheric data obtained from Cape Town International Airport, as well as sea-surface temperatures, topography, vegetation and soil data. Modeled values of relative humidity were calculated for each hour of the day for each day of February 2000 and hourly mean values were then determined for these parameters for the 1 km grid (Bonnardot and Cautenet, 2008). These authors found that the modeled values for the 1 km grid were a good representation of the actual values determined at the automatic weather stations. The grid was then integrated into the GIS database.

The 55 to 60 % relative humidity category appeared to represent this sea breeze « front » as its profile was affected both by the inflowing moist air from the ocean and the dry inland air. This front represents modeling for a single month (February, 2000), and can not be considered definitive, especially knowing that the topic is highly emotive amongst wine producers and holds quality connotations in the market place as it is associated with cooler ripening conditions. A conservative estimate of the extent of the sea breeze effect was made using the 50 % isoline as a guide. This erred on the side of inclusivity, probably including a larger area than may actually be affected, so as to accommodate potential variability of a spatial (variation at a scale more detailed than a 1 km grid represents) and temporal (variation that may be caused by inclusion of data from other months during the ripening period and other years than 2000) nature. Approximately one half of the Stellenbosch Wine of Origin District was included within the area that was considered to be affected by the sea breeze (figure 4).

Identification of Natural Terroir Units

The environmental variables of aspect, altitude, terrain morphological units, soil and geology, were divided into classes (table III). Shape files were converted into rasters (50 m grid), where necessary, using Spatial Analyst™ in ESRI®ArcMap™ 8.2 software. The terrain morphological units, aspect, altitude and soil classes, were combined into homogenous units (soil-landscape units) using the Raster Calculator in Spatial AnalystT™ in ESRI®ArcMap™ 8.2 software. This was achieved by allocating to each class of each variable an integer, making use of multiples of 10 000 (terrain morphological units), 1 000 (aspect), 100 (altitude) and 1 (soil). Addition of these variables resulted in each grid cell being allocated a value, which formed a code representing the class of terrain morphological unit, aspect, altitude and soil (e.g. midslope terrain morphological position + SW aspect+ 300-400 m altitude + stony freely drained structureless soils would be 30 000 + 4 000 + 400+ 03 = 34 403 or mSW4Bs, table III). Boundaries were drawn around areas with identical values to identify homogenous units.

Geology was only considered to be of relevance for soils falling within the classes of residual soils, freely drained structureless soils and dry duplex soils (see table II). As it was not sufficiently detailed, it was included by calculating the median for each relevant « soil-landscape » unit using zonal statistics in Spatial Analyst™ in ESRI®ArcMap™ 8.2. software. Furthermore, a prefix of « s » was added if the NTU fell within the identified « limit » of the sea breeze influx.

Validation

Forty-eight vineyards, representing various positions in the landscape, were used to examine the validity of the identified natural terroir units. Altitude and aspect were determined from 1:10 000 orthophotos obtained from the Chief Directorate: Surveys and Mapping. The terrain morphological position was described *in situ*, and due to difficulty of estimation, was compared to position on 1:10 000 orthophotos and corrected if need be. Backhoe pits of at least 1 m depth were dug in vineyards parallel with the vineyard rows. Soil profiles were classified using the South African Taxonomic system (Soil Classification Working Group, 1991) and the geological origin of the parent material was estimated by an experienced soil scientist (D Saayman 2000, personal communication).

Significance of identified Natural Terroir Units for viticulture

A map of vineyards, that was compiled from a classification of Landsat™ images (Capture date 23 November 2001), was obtained from the Geoinformatics Division of ARC Institute for Soil, Climate and Water. This map (figure 3f) was used to determine the area of each topographic, soil and geological class and natural terroir unit that was planted to grapevines in 2001 with the aid of ESRI®ArcMap™ 8.2. software.

RESULTS AND DISCUSSION

Climate

All climatic variables differed significantly between weather stations and between seasons (table I). The mean temperature of the warmest month (February) varied between 21.0 and 22.7 °C in Stellenbosch (table I). The effect of the penetration of the sea breeze on summer temperatures results in both a delay and a reduction in the daily maxima (Bonnardot *et al.*, 2001). In table I, it is noticeable that the automatic weather stations that are either placed at altitude (T02, T03, and T27) or within the limits of the sea breeze effect (T06, T08 and T10) record the coolest maximum temperatures during February. The warmest air lies in the Stellenbosch and Eerste River Valleys, reflected in the high February mean maximum temperatures recorded at weather stations T21 and T25.

Temperature-related indices were also determined for each of the weather stations in the Stellenbosch Wine of Origin District (table I). Nine of the 17 weather stations fall within Class III for the thermal-time index of Amerine & Winkler (1944) (adapted for the South Western Cape by Le Roux, 1974). The weather stations at T04, T12, T13, T14, T16, T21, T25 and T26 fall within Class IV. The classification of T13 and T14 is surprising, as these weather stations are in positions relatively near to the coast (figure 1) and theoretically fall within the extent of the sea breeze effect. They may, however, be influenced by microclimatic conditions in their immediate proximity. The other weather stations classified in class IV all fall outside the theoretical limit of the sea breeze influence. For the Huglin Index, where the maximum temperature has a heavier weighting, only T04, T12, T21 and T25, the weather stations positioned outside the limits of the sea breeze effect, fall within Class +2 (Tonietto and Carbonneau, 2004), which suggests that weather stations T13 and T14 do, indeed, benefit from the moderating influence of the sea breeze. Class +2 suggests that there may be periods of high temperature stress during ripening (Tonietto, 1999; Tonietto and Carbonneau, 2004). All weather stations are classified as having a moderate temperature during February (De Villiers *et al.*, 1996), the warmest month, and as having temperate nights (class -1) (Tonietto and Carbonneau, 2004).

The annual rainfall measured in the Stellenbosch Wine of Origin District varies between 549 mm at T05 (Devon Valley) and 961 mm at T02 (Helshoogte) (table 1 and figure 2), with a typically Mediterranean distribution of dominant winter rainfall. The rainfall during the period December to February (ca. véraison to harvest) ranges between 52 mm at T10 and 98 mm at T12. This results in arid conditions during ripening and the Dryness Index calculated for all the stations falls within the category « very dry », i.e. Class +2 (Tonietto and Carbonneau, 2004) (data not shown). This results in frequent drought stress events in vineyards, necessitating the use of irrigation in many cases to ensure the ripening of grapes of high quality.

The atmospheric relative humidity of the Stellenbosch Wine of Origin District is strongly affected by the movement of the sea breeze. The cool, moist air associated with the sea breeze moves along the coast and across the Bottelaryberg in the early afternoon, while the warm, dry inland air moves down the Eerste River Valley. This is, however, not reflected in the mean monthly minimum relative humidity values measured at the agroclimatic weather stations (table I). Rainfall during February would also have strongly affected these values. The agroclimatic stations where high rainfall values were recorded for the period December to February, e.g. T02, T12 and T16, also recorded higher mean minimum relative humidity values for February (table 1). The agroclimatic stations T25 and T27, both outside the limit of the sea breeze, did, however, record exceptionally low minimum relative humidity values (33.6 and 38 % respectively) during February.

Because of the high significance of the inter-annual climatic variation, as has also been shown in Bordeaux (Van Leeuwen *et al.*, 2004), climate cannot be considered to be a stable environmental parameter, particularly in the light of recorded (Bonnardot and Carey, 2007) and predicted (Carter, 2006) global climate change. Within a given macro-climatic scenario (for example a specific season), mesoclimatic variation will be determined by landscape attributes (topographic position, proximity to large bodies of water, etc.), as is shown by the above climatic analyses. As the concept of « natural terroir units » focuses on a stable group of environmental variables, it was decided to focus on the more stable environmental features to determine these homogenous units.

Topography

Within the Stellenbosch Wine of Origin District, 26.4 % of the surface area is classified as crest, 40.4 % as mid-slope, 22.8 % as foot-slope and 10.4 % as valley bottom. Overlaying the map of vineyards on the spatial topographic data layers showed that 34 % of vineyards are found on crest positions, 45 % on midslope positions, 18 % on footslope positions and 3 % in valley bottoms. Sixty-seven percent of the surface of the Wine of Origin District has a slope of less than 15 %, whereas 96 % of the vineyards are planted on slopes less than 15 %. Just short of 100 % of the vineyards in the Stellenbosch Wine of Origin District are situated below 500 m and ca. 51 % are cultivated between 100 m and 200 m. Approximately 45 % of the vineyards are found on aspects classified as NW, and 39 % on those classified as SW, with the remainder on E slopes. The percentage of the n=48 vineyards that were found to be accurately classified when compared to the digital data layers was 72 % for the terrain morphological units, 94 % for altitude and 88 % for aspect. The faults may not wholly lie with the spatial data but may also reside in the description of the vineyard sites. The terrain morphological units had the least accurate prediction and this seemed to be often related (in 71 % of the erroneous cases) to the prediction of a crest instead of the visually-determined terrain morphological unit. This appears to be due to downward sloping ridges being classified as crests by the spatial model but rather as midslopes or footslopes in the field or with the aid of orthophotos.

Soil

Vineyards in the Stellenbosch Wine of Origin District were found to be predominantly cultivated on red and yellow, freely-drained, structureless or weakly structured soils and medium-deep wet duplex soils (figure 5). Red and yellow, freely-drained, structureless or weakly structured soils are strongly associated with midslope positions, while the medium-deep wet duplex soils are more commonly associated with footslope positions. Well-drained conditions, caused by the slope gradient and form in midslope positions, result in an oxidising environment that gives red-brown to yellow-brown colours to iron oxides coating soil particles (Soil Classification Working Group 1991). These soils are intensely weathered and are relics of a past, high rainfall, tropical era (the Eocene). There is an almost complete loss of basic cations and much of the silica content due to drainage and leaching, resulting in generally acidic, stable, well-drained soils with a low base status and a good water-holding capacity (Lambrechts, 1983). Footslopes are concave and have lower gradients, resulting in increased sediment accumulation (Wysocki *et al.*, 2000). This sediment may be of sandstone or granitic origin and may have been alluvially or colluvially transported. It may also represent plain remnants of the Malmesbury Group (Schloms *et al.*, 1983). With the basement rock in these landscape positions being of a shale origin and the colluvium or alluvium being generally of a granitic or sandstone origin, the soils that developed have a coarsely textured topsoil, usually bleached, on a subsoil with a high clay content and signs of water inundation, the so-called duplex soils (Soil Classification Working Group, 1991). Duplex soils may also consist of coarsely textured topsoil on strongly structured subsoil. In these soils, the subsoil has a blocky to prismatic structure, with the presence of obvious cutans on the soil peds or stones due to the enrichment of the horizon with clay by means of illuviation (Soil Classification Working Group, 1991).

Geology

Vineyards in the Stellenbosch Wine of Origin District were found to be cultivated predominantly on *in situ* weathering products of granite (gravelly clay) or granite, although also, to a considerable extent, on shale derived materials (figure 6).

Natural terroir units

As mentioned in previous sections, soil depth and type are closely related to landscape position. One climatic aspect of particular interest is the occurrence of the sea breeze, the penetration of which is linked to the topography of the coastal area. Climatic variables per se were not included as defining variables for natural terroir units in the Stellenbosch Wine of Origin District, but rather the static variables that influence the mesoclimate. Topography, and in particular elevation, aspect and terrain morphological unit were expected to play a central role in integrating the environmental characteristics of the Stellenbosch Wine of Origin District.

Using the environmental variables given in table III, a total of 1389 natural terroir units (NTUs) were identified

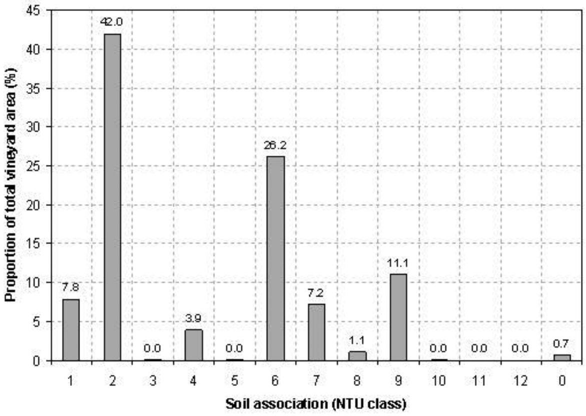

Figure 5 - Soil class expressed as a percentage of the area cultivated under grapevines in the Stellenbosch Wine of Origin District (2001). Soil association classes are described in tables II and III.

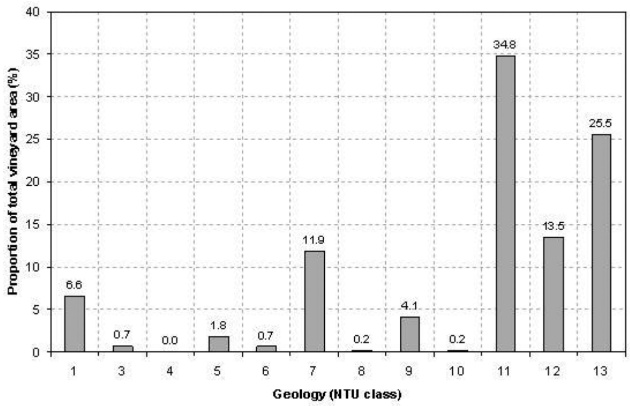

Figure 6 - Geological class expressed as a percentage of the area cultivated under grapevines in the Stellenbosch Wine of Origin District (2001). Geological classes are explained in table III.

Table IV - Predicted natural terroir units and determined topographic and soil parameters for selected vineyards in the Stellenbosch Wine of Origin District.

Vineyard	NTU[1]	TMU	Aspect	Altitude	Soil[2]
T01CH	mSW2B-Qg	Midslope/Footslope	SW	167	Swartland[3]
T01CS	mSW2B-Qg	Midslope/Footslope	WSW	164	Klapmuts[3]
T01SB	cSW2B-Tygerberg	Midslope/Footslope	SW	167	Swartland[3]
T02CH	s_cSW5B-Qgg	Midslope	SSE	440	Oakleaf
T02CS	s_mE4B-Qgg	Midslope	NE	375	Tukulu
T03CH	cNW4B-Granite	Crest/Midslope	NW	380	Oakleaf
T03CS	MNW3B-Qgg	Midslope	NNW	282	Tukulu
T04CH	s_cNW2B-Qgg	Crest	W	172	Oakleaf
T04CS	s_cSW2B-Qgg	Midslope	WSW	178	Oakleaf
T05CH	s_fE2B-Qgg	Midslope	NE	185	Oakleaf
T05CS	s_cNW3B-Tygerberg	Midslope	NW	198	Oakleaf
T06CH	s_cSW3B-Granite	Crest/Midslope	WSW	222	Sepane
T06CS	s_cSW3B-Granite	Crest/Midslope	WSW	213	Swartland
T08CH	s_cNW3B-Granite	Midslope	WNW	235	Swartland
T08CS	s_fE2B-Qgg	Footslope	NE	183	Vilafontes
T08SB	s_mNW2D	Midslope	NW	185	Oakleaf
T09CS	s_cNW1D	Footslope	N	97	Klapmuts
T09SB	fE2D	Footslope	NW	90	Klapmuts
T10CH	s_cSW2B-Tygerberg	Ridge/Midslope	SSE	122	Clovelly
T10CS	s_cSW2B-Tygerberg	Ridge/Midslope	SSW	161	Klapmuts
T10SB	s_cSW2D	Midslope	SW	142	Klapmuts
T12CS	s_mNW3B-Granite	Midslope	NW	218	Tukulu
T13CH	s_mSW1D	Midlsope/Footslope	WSW	39	Westleigh
T13CS	s_mSW1D	Midslope	WSW	56	Kroonstad
T13SB	s_fSW1F+G	Valley bottom		32	Westleigh
T14CH	s_fSW1Dv	Valley bottom	SE	16	Dundee
T14CS	s_cE1Dv	Footslope		18	Estcourt
T14SB	s_mNW1Dv	Valley bottom	SE	16	Dundee
T15CH	s_cSW2B-Qgg	Midslope	SSW	155	Oakleaf
T15CS	s_mSW2B-Qgg	Midslope	SSW	132	Oakleaf
T15SB	s_fSW2B-Alluvium	Midslope	SSW	128	Oakleaf
T16CH	mE3B-Qgg	Midslope/Footslope	NE	259	Tukulu
T16CS	mE3B-Qgg	Midslope	NW	283	Oakleaf
T16SB	mE3B-Qgg	Midslope/footslope	NE	255	Westleigh[4]
T21CH	cNW2D	crest/Midslope	NE	197	Oakleaf
T21CS	mNW2D	Midslope	NE	190	Oakleaf
T21SB	mNW2D	Midslope	NNE	186	Tukulu
T23CH	cSW3A-Qgg	Midslope/Footslope	SW	196	Avalon
T23CS	cSW3B-Qgg	Footslope	WSW	233	Tukulu
T23SB	cSW3A-Qgg	Midslope/Footslope	WSW	207	Tukulu
T24CH	fSW3B-Franschoek	crest/Midslope	SW	261	Tukulu
T24CS	cNW3D	crest/Midslope	NW	290	Tukulu
T24SB	fSW3Dv	Crest	WSW	242	Swartland[3]
T25CH	s_fNW1F+G	Footslope	N	93	Kroonstad[5]
T25CS	s_cNW2B-Qgg	Plateau/Midslope	NNW	130	Klapmuts[6]
T26CH	s_mNW4B-Tygerberg	Midslope	WNW	320	Oakleaf
T26SB	s_mSW3A-Alluvium	Midslope	SW	247	Klapmuts
T27CS	mNW4B-Qgg	Midslope/Footslope	WSW	383	Westleigh[3]

1 This column must be interpreted together with table III

2Soil forms of the South African Taxonomical Soil Classification system (Soil Classification Working Group, 1991). Interpret together with table II

3Transitional soil form: Tukulu

4This soil could also possibly be classified as Tukulu

5This soil can reasonably be grouped in class 9 (table II)

6Transitional soil form: Vilafontes

Table V - Ten most prominent natural terroir units for viticulture in the Stellenbosch Wine of Origin District, South Africa.

NTU code	Characteristics	Area (ha)	Proportion of vineyard area (%)
mNW2D	North-westerly oriented midslopes between 100 m and 200 m altitude, with medium-deep, wet, duplex soils. Located outside the extent of influence of the sea breeze.	402.8	3.0
s_mSW2B	South-westerly oriented mid-slope positions between 100 m and 200 m altitude, with freely-drained, structureless or weakly structured soils. Located within the extent of influence of the sea breeze.	394.0	2.9
mSW2D	South-westerly oriented midslope positions between 100 m and 200 m altitude, with excessively medium-deep, wet, duplex soils. Located outside the extent of influence of the sea breeze.	343.1	2.6
mNW3B	North-westerly oriented midslope positions between 200 m and 300 m altitude, with freely-drained, structureless or weakly structured soils. Located outside the extent of influence of the sea breeze.	284.2	2.1
s_cSW2B	South-westerly oriented crest positions between 100 m and 200 m altitude, with freely-drained, structureless or weakly structured soils. Located within the extent of influence of the sea breeze.	276.3	2.1
s_mNW2B	North-westerly oriented midslope positions between 100 m and 200 m altitude, with freely-drained, structureless or weakly structured soils. Located within the extent of influence of the sea breeze.	268.2	2.0
s_mE2B	Easterly oriented midslope positions between 100 m and 200 m altitude, with freely-drained, structureless or weakly structured soils. Located within the extent of influence of the sea breeze.	259.3	1.9
s_mNW2D	North-westerly oriented mid-slope positions between 100 m and 200 m altitude, with medium-deep, wet, duplex soils. Located within the extent of influence of the sea breeze.	255.6	1.9
cNW3B	North-westerly oriented crest positions between 200 m and 300 m altitude, with freely-drained, structureless or weakly structured soils. Located outside the extent of influence of the sea breeze.	238.7	1.8
s_cNW3B	North-westerly oriented crest positions between 200 m and 300 m altitude, with freely-drained, structureless or weakly structured soils. Located within the extent of influence of the sea breeze.	220.5	1.7

in the Stellenbosch Wine of Origin District. The units were also characterized with respect to dominant geological formations and effect of the sea breeze during February.

Ground-truthing, by comparing field observations of characteristics of experimental plots in commercial vineyards with the identified NTUs, showed a 63 % success rate (excluding geology) (table IV). The failure to match field characterization with GIS characterization was mainly due to lack of agreement between soil types (71 % of cases corresponded with predicted soil type, table IV) and/or terrain morphological units (72 % of cases corresponded with predicted terrain morphological unit, table IV).

Only 466 terrain morphological units had a surface area of greater than 25 ha. In 2001, grapevines were cultivated on 778 of the identified NTU. Of these, 302 natural terroir units had a surface of greater than 25 ha.

The 10 most prominent natural terroir units for viticulture and their characteristics are shown in table V. The descriptor of geology was excluded so as not to unfairly weight the soil types. For each of these natural terroir units, a particular potential for viticulture can be associated based on the topographical and soil characteristics. The dominant natural terroir unit, mNW2D, is expected to have a warmer, protected mesoclimate, with soils that may restrict root growth and result in water stress later in the season. These sites will, therefore, probably benefit from irrigation during the season. In contrast, the natural terroir unit s_mSW2B, would be expected to have a cooler mesoclimate, exposed to influx of cool, moist air during the afternoon. The soil would be expected to be well-drained but with a good water-holding capacity. The functioning of the grapevine is an important component of the terroir complex (Deloire *et al.*, 2005) and it is, therefore, important to study the response of the grapevine and the style of the final, transformed product, wine, so as to have a clear understanding of which natural terroir units will result in an identifiable product.

CONCLUSIONS

The Stellenbosch Wine of Origin District is characterized by a Mediterranean climate that varies spatially in relation to the local topography and exposure to the influence of the ocean. Vineyards are closely associated with the midslopes and footslopes of the mountains and hills of the region. In these positions varying soil types, related to varying geological, parent material can be found. These determine varying site potential for viticulture.

Relevant topographic features can be determined from a digital elevation model and soil association data is available at a suitable scale. Geological data is, however, only available at a reconnaissance level. Similarly, the extent of the sea breeze influence is not easy to determine but can be estimated from climatic modeling.

Natural terroir units have integrated environmental factors affecting wine character and style. They provide information in addition to what would be available from a map of soil associations. This additional information is of value for viticulture, as topography and proximity to the ocean affect wind exposure, air humidity and temperature and geology affects the mineral composition, soil texture, water regulating properties and availability of soil nutrients. The number of natural terroir units for the Stellenbosch Wine of Origin District is, however, myriad and many of them are of a size that is not economically or practically viable. They have also not yet been directly linked with the functioning of the grapevine or the characteristics of the final, transformed product, although, knowledge and experience of the reaction of the grapevine to a particular environmental variable, notably climate and soil, may assist in estimating viticultural and oenological potential of a natural terroir unit from the information presented in its code. Further determination of their viticultural and oenological aptitude should assist in the grouping of natural terroir units with similar aptitudes into larger, more viable units. This will be addressed in subsequent companion papers.

Acknowledgements: This publication is based on research that was financially supported by the Agricultural Research Council, Stellenbosch University, Winetech and the National Research Foundation under grant number 2053059. The research infrastructure was provided by Arc Infruitec-Nietvoorbij. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of these organizations.

Thanks are due to Dalene Opperman, Francois Knight and Ryk Taljaard for assistance with the creation of digital data layers. This paper formed part of a PhDAgric dissertation presented by the first author and the comments of Prof. P.G. Goussard, Prof. Emmanuelle Vaudour and Dr W.J. Conradie, examiners of this dissertation, are gratefully acknowledged. Furthermore, the helpful comments of anonymous reviewers, that have contributed to an improved paper, are acknowledged.

REFERENCES

Bonnardot V.M.F., 1997. Effect of the sea-breeze on the temperature in the Stellenbosch-Klein Drakenstein wine-producing district. *Report for ARC Infruitec-Nietvoorbij*, Private Bag X5026, 7599 Stellenbosch, South Africa.

Bonnardot V.M.F., 1999. Étude préliminaire des brises de mer pendant la période de maturation dans la région viticole du Cap en Afrique du Sud. *Association internationale de climatologie*, **12**, 26-33.

Bonnardot V. and Cautenet S., 2008. Mesoscale atmospheric modeling using a high horizontal grid resolution over a complex coastal terrain and a wine region of South Africa. *J. Appl. Met. Clim.,* **47**, 19 p.

Bonnardot V., Planchon O., Carey V. and Cautenet S., 2002. Diurnal wind, relative humidity and temperature variation in the Stellenbosch- Groot Drakenstein wine growing area. *S. Afr. J. Enol. Vitic.*, **23** (2), 62-71.

Buys M.E.L., 1971. The use of electronic aids and statistical techniques in the evaluation of the agroclimate of the South Western Cape [In Afrikaans: Die gebruik van elektroniese hulpmiddels en statistiese tegnieke in die evaluering van die agroklimaat in die Suidwes Kaapland.] *PhD Thesis*, Stellenbosch University.

Carey V.A., 2001. Spatial characterisation of natural terroir units for viticulture in the Bottelaryberg-Simonsberg-Helderberg winegrowing area. *MScAgric Thesis*, Stellenbosch University.

Carrega P., 1995. Approches de la structure thermique et hygrométrique d'une brise de mer par mesures aéroportées. *Groupement de recherche Climat et Santé*, 165-175.

Carter S., 2006. The projected influence of climate change on the South African wine industry. *IIASA Interim Report*, IR-06-043, 33 pp.

Conradie W.J., Carey V.A., Bonnardot V., Saayman D. and Van Schoor L.H., 2002. Effect of different environmental factors on the performance of Sauvignon blanc grapevines in the Stellenbosch/Durbanville districts of South Africa. I. Geology, soil, climate, phenology and grape composition. *S. Afr. J. Enol. Vitic.*, **23** (2), 78-91.

Cotton W.R., Pielke Sr R.A., Walko R.L., Liston G.E., Tremback C.J., Jiang H., McAnely R.L., Harrington J.Y., Nicholls M.E., Carrio G.G. and McFadden J.P., 2003. Rams 2001: Current status and future directions. *Meteorol. Atmos. Phys.*, **82**, 5-29.

Crowe P.R., 1971. *Concepts in Climatology*. Longman Group Limited, London.

De Blij H.J., 1983. *Wine. A geographic appreciation*. Rowman and Allanheld, New Jersey.

Deloire A., Vaudour E., Carey V., Bonnardot V. and Van Leeuwen C., 2005. Grapevine responses to terroir: a global approach. *J. Int. Sci Vigne Vin*, **39** (4), 149-162.

Ellis F. and Schloms B., 1975. *Reconaissance soil survey of the Eerste River catchment area. Stellenbosch. [Title in Afrikaans: Verkenningsgrondopname van die Eersterivieropvanggebied. Stellenbosch.]* Scale 1:25 000. Reg. No. 11296/1, SIRI, Department of Agricultural Technical Services, Pretoria.

Ellis F., Rudman R., Smith-Baillie A., Oosthuizen A. and Schloms B., 1976. *Reconaissance survey of the Berg River catchment area. Franschoek to Riebeeck West. [Title in Afrikaans: Verkenningsgrondopname van die Bergrivieropvanggebied. Franschoek tot Riebeeck-Wes].* Scale 1:50 000. Reg. No. 11440, SIRI, Department of Agricultural Technical Services, Pretoria.

Ellis F., Schloms B.H.A., Rudman R.B. and Oosthuizen A.B., 1980. *Soil association map of the Western Cape (preliminary compilation). [Title in Afrikaans: Grondassosiasie kaart van die Weskaap (Voorlopige kompilasie)].* Scale 1:250 000. Reg: No. 12042, SIRI, Department of Agriculture and Water Supply, Pretoria.

ESRI (Environmental Systems Research Institute Inc), 2000. ArcView 3.2 Help File Documentation. Redlands, California.

Gladstones J., 1992. *Viticulture and Environment*, Winetitles, Adelaide.

Huglin P., 1983. Possibilités d'appréciation objective du mileu viticole. *Bull. OIV*, **56**, 823 833.

Kruger G.P., 1973. *Concepts, techniques and procedures for the global resource survey program (terrain) [Title in Afrikaans : Konsepte, tegnieke en prosedure vir die globale hulpbronopnameprogram (terrein]*. SIRI Report No. 154/73/784'. Department of Agricultural Technical Services, Pretoria.

Land Type Survey Staff, 1972-1999. *Memoirs of the Agricultural Natural Resources of South Africa*. Institute for Soil, Climate and Water, Pretoria.

Laville P., 1993. Unités de terroir naturel et terroir. Une distinction nécessaire pour redonner plus de cohérence au système d'appellation d'origine. *Bull OIV*, **745/746**, 227-251.

Le Roux E.G., 1974. A climatic categorisation of the South Western Cape wine producing areas [Title in Afrikaans: 'n Klimaatsindeling van die Suidwes-Kaaplandse Wynbougebiede] *MScAgric Thesis*, Stellenbosch University.

MacVicar C.N., Scotney D.M., Skinner T.E., Niehaus H.S. and Loubser J.H., 1974. A classification of land (climate, terrain form, soil) primarily for rainfed agriculture. *S. Afr. J. Agric. Extension*, **3**, 22-24.

Morlat R., 1996. Éléments importants d'une méthodologie de caractérisation des facteurs naturels du terroir, en relation avec la réponse de la vigne à travers le vin. *In : 1st International Colloquium Les terroirs viticoles : Concept, produit, valorisation*. I.N.R.A., Angers/Montpellier, p. 17-31.

Pielke R.A., Cotton W.R., Walko R.L., Tremback C.J., Lyons W.A., Grasso L.D., Nicholls M.E., Moran M.D., Wesley D.A., Lee T.J. and Copeland J.H., 1992. A comprehensive meteorological modeling system- RAMS. *Meteorol. Atmos. Phys.*, **49**, 69-91.

Riou C., Morlat R. and Asselin C., 1995. Une approche intégrée des terroirs viticoles. Discussions sur les critères de caractérisation accessibles. *Bull. OIV*, **68**, 93-106.

Saayman D., 1976. Crop production in the light of soil classification [Title in Afrikaans: Gewasproduksie in die lig van grondklassifikasie: Wyndruiwe]. *Fert. Soc. S.A.J.* **1**, 53-58.

Saayman D., 1977. The effect of soil and climate on wine quality. *In: International symposium on quality of the vintage.* Oenological and Viticultural Research Institute, Stellenbosch, p. 197-206.

Saayman D. and Kleynhans P.H., 1978. The effect of soil type on wine quality. *In: South African Society for Enology and Viticulture congresss*. South African Society for Enology and Viticulture, Stellenbosch, p. 105-119.

SAWIS (SA Wine Industry Information & Systems), 2002. South African Wine Industry Statistics 26. SAWIS, Paarl.

Schultz R.E., 1997. South African Atlas of Agrohydrology and -Climatology. Water Research Commission, Pretoria, Report TT82/96, University of Natal, Pietermaritzburg.

Soil Classification Working Group, 1977. Soil Classification. A binomial System for South Africa. Memoirs on the Agricultural Natural Resources of South Africa, n° 15, Department of Agricultural Information, Pretoria.

Soil Classification Working Group, 1991. Soil Classification. A taxonomic system for South Africa. Memoirs on the agricultural natural resources of South Africa, n° 55. Department of Agricultural Development, Pretoria.

Theron J.N., 1990. Geological Survey. 1:250 000 series. Sheet 3318 Cape Town. The Government Printer, Pretoria.

Theron J.N., Gresse P.G., Siegfried H.P. and Rogers J., 1992. The *Geology of the Cape Town Area. Explanation of Sheet 3318.* Scale 1:250 000. Department of Mineral and Energy Affairs, Pretoria.

Van Schoor L., 2001. Geology, particle size distribution and clay fraction mineralogy of selected vineyard soils in South Africa and the possible relationship with grapevine performance. *MScAgric Thesis*, Stellenbosch University.

Van Zyl J.L. and Van Huyssteen L., 1979. The categorisation of soils according to their potential for wine grapes with particular reference to the Upper Berg River valley. [Title in Afrikaans: Die indeling van gronde volgens potensiaal vir wyndruiwe met spesiale verwysing na die Bo-Bergriviervallei]. *Wynboer*, July, 55-61.

Wooldridge J., 1988. The potassium supplying power of certain virgin upland soils of the Western Cape. *MScAgric Thesis*, Stellenbosch University.

Wooldridge J., 2000. Geology: A central aspect of terroir. *Wynboer,* **137**, 87-90.

Wooldridge J., 2003. Geology and terroir in the Western Cape winelands. *Wynboer*, **173**, 85-87.

Wooldridge J. and Beukes H., 2003. Topography and solar interception in the Stellenbosch district. A geographic information systems approach. Part I. Landscape, slope and aspect. *Wynboer*, **163**, 74-76.

Wysocki D.A., Schoeneberger P.J. and LaGarry H.E., 2000. Geomorphology of soil landscapes. E-5 - E-35. *In: Handbook of Soil Science*. Ed. Sumner M.E., CRC Press, United States.