VITICULTURAL TERROIRS IN STELLENBOSCH, SOUTH AFRICA. III. SPATIALISATION OF VITICULTURAL AND OENOLOGICAL POTENTIAL FOR CABERNET-SAUVIGNON AND SAUVIGNON BLANC BY MEANS OF A PRELIMINARY MODEL

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

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

Abstract

Aims: Identification and characterisation of terroirs depends on knowledge of environmental parameters, functioning of the grapevine and characteristics of the final product. Field studies, resulting in point data, are necessary to investigate the functioning of the grapevine but in order for this information to be of use within zoning studies it must be placed in a spatial context.

Methods and results: A knowledge-driven model used the rules generated in regression tree analyses to directly classify natural terroir units with respect to expected response of Cabernet-Sauvignon and Sauvignon blanc in the Stellenbosch Wine of Origin District. The natural terroir units were then grouped into terroir units that were homogenous with respect to predicted response of selected viticultural and oenological variables for each studied cultivar.

Conclusions: The use of regression tree methodology (CART analyses) enabled the definition of decision trees for spatialisation of this data. Each natural terroir unit could be evaluated with respect to its potential viticultural and oenological response and thus grouped to identify terroir units.

Significance and impact of the study: The identified terroir units can only be considered preliminary but the methodology used has promising implications for different scales of study.

Key words: terroir, zoning, Cabernet-Sauvignon, Sauvignon blanc, soil, climate

Résumé

Objectifs : L'identification et la caractérisation des terroirs viticoles dépendent de la connaissance des paramètres de l'environnement, du fonctionnement de la vigne et du produit final. Les études au vignoble sont nécessaires pour comprendre le fonctionnement de la vigne, et pour que les données acquises puissent être utilisées dans le cadre d'un zonage, il faut qu'elles soient spatialisées.

Méthodes et résultats : Un modèle d'acquisition de connaissances utilisant la représentation en arbre de décision a été utilisé pour classer les unités naturelles de terroir pour le Cabernet-Sauvignon et le Sauvignon blanc dans la zone viticole d'appellation d'origine de Stellenbosch. Les unités naturelles de terroir ont été groupées en unités homogènes, en accord avec le comportement de la vigne et le type de vin, pour chacun des deux cépages étudiés.

Conclusions : L'utilisation des arbres de décisions (analyses CART) permet de spatialiser les données acquises. Chaque unité naturelle de terroir peut être évaluée en accord avec son potentiel viticole et œnologique et les unités peuvent alors être groupées en unités homogènes identifiables.

Signification et impact de l'étude : Les unités de terroir identifiées le sont à titre préliminaire, mais la méthode utilisée a des implications intéressantes pour les études de terroir à différentes échelles.

Mots-clés : terroir, zonage, Cabernet-Sauvignon, Sauvignon blanc, sol, climat

manuscript received the 27th of August 2007 - revised manuscript received the 28th August 2008

*Corresponding author: vac@sun.ac.za

INTRODUCTION

A terroir can be defined as a natural unit that is characterised by a specific agricultural potential. The agricultural potential is imparted by natural environmental features, and is reflected in the characteristics of the final product (Dubos, 1984, Seguin, 1986, Morlat, 1989, Laville, 1993). The definition of terroir includes, in many cases (Morlat 2001, Deloire *et al.* 2005), the « human factor » or the viticultural and oenological practices contributing to the final product. Laville (1993), however, suggested that it is a mistake to include human practices and plant material in the definition of terroir as these should constantly evolve as a result of continuous experimentation, as is indeed the case in the Stellenbosch district, study area of the research presented in this publication. Identification and characterisation of terroirs depends, in cases such as these, on knowledge of environmental parameters, functioning of the grapevine and characteristics of the final product. Because the terroir concept relies on the intrinsic agronomic potential of the environment, and is inseparable from the characteristics and « identity » of the final agricultural product, all studies to delimit terroirs should include mapping of pertinent environmental features in order to obtain relatively homogenous environmental units, as well as a study of the reaction of the crop to these delimited units (Morlat, 2001, Vaudour, 2003). It is necessary to determine a hierarchy for the environmental factors with respect to their relevance to viticulture in the region, as well as to determine rules that may be used for spatialisation of the results. The criteria selected for viticultural zoning of terroirs must be pertinent with respect to grapevine physiology and fruit biochemistry, have a compatible spatial variability and be easily acquired in the field (Riou *et al.*, 1995). Environmental variables that should be considered include those of climate (rainfall, radiation, air temperature, soil temperature, direction and intensity of dominant winds, evapotranspiration), relief or geomorphology (altitude, slope, exposition, insolation, slope form), substrate or geology and soil (mineralogy, structure, granulometry, soil water regulation and/or availability, depth, colour) (Laville, 1993).

In order to determine the functioning of the grapevine and the characteristics of the final product on a particular natural terroir unit, it is necessary to perform in situ studies resulting in point data, but in order for this information to be of use within zoning studies, it must be placed within the context of the pertinent terroir in order to provide a spatial result (Vaudour, 2000 ; Vaudour, 2001). An environmental model to identify terroirs, therefore, consists of various logical arguments and processing methods. The first stage will generally consist of an empirical (i.e. deterministic) inductive model. Inductive arguments are evidence based (Skidmore, 2002). Field data are explored for possible patterns that can be used to derive a general statement with respect to viticultural or oenological response. Such data-driven statistical models are called « empirical » (Skidmore, 2002). Actual experience is used to substantiate beliefs. Statistical methods such as Classification and Regression Trees (CART) (Breiman *et al.*, 1984 ; Skidmore, 2002) derive thresholds that can be used in empirical models. The second stage encompasses a knowledge-driven deductive model. A deductive argument is one that draws a specific conclusion from a set of general propositions that have been based on plausible physical laws (Skidmore, 2002). Knowledge driven models use rules generated from expert opinion or statistical induction (e.g. CART) to summarise relationships between dependent and independent variables, which can then be used to directly classify unknown spatial objects by deduction (Skidmore, 2002).

The first paper in this series detailed the delimitation of natural terroir units in the Stellenbosch Wine of Origin District and dealt with generation of a spatial data layer of natural terroir units with « unknown » aptitude for viticultural and oenological performance. The second paper discussed an investigation into the reaction of *Vitis vinifera* L. cvs. Cabernet-Sauvignon and Sauvignon blanc to site environment. Regression trees were used to detail premises that can be used to derive statements or rules for further deductive arguments. This third paper has as its objective the integration of the natural terroir units (NTUs) and the response of the grapevine (as determined by selected viticultural and oenological variables) using a knowledge-driven deductive model to determine viticultural terroirs for the production of Cabernet-Sauvignon and Sauvignon blanc grapes for wine production in the Stellenbosch Wine of Origin District.

MATERIALS AND METHODS

1. Study area

The study area covered the Stellenbosch Wine of Origin District situated at ca. 34°S, 19°E (figure 1).

2. Identification of natural terroir units

Natural terroir units were, in this study, considered to be land units that are practically homogenous with respect to terrain morphological unit, slope aspect, altitude, and broad soil category. They have further descriptors of geology for pertinent soil types and extent of sea-breeze effect. The procedure and data used to identify natural terroir units were described in a companion paper (Carey *et al.*, 2008a).

3. Field studies

Reference plots of Cabernet-Sauvignon and Sauvignon blanc were delimited in commercial vineyards in 1995 in proximity to weather stations (figure 1). The study continued for a period of seven years (1995-2002). The viticultural and oenological measurements are outlined in detail in Carey *et al.*, 2005b).

4. Digital data

A 50 m Digital Elevation Model (DEM) was used to determine elevation and slope inclination using Spatial AnalystTM in ESRI®ArcMap™ 8.2. 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. 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. The scale of these data held limitations for a study at the district level but were the best available.

Spatial climatic interpolations from a seven-year series of data from the automatic weather station network were obtained (table 1) (F Knight, Agri Informatics, unpublished data, 2004).

5. Determination of the response of Cabernet-Sauvignon and Sauvignon blanc to the site environment

Regression tree methodology (Breiman *et al.*, 1984) was used to derive decision trees for each dependent variable and the hierarchy of environmental and management related variables that affected the performance of Cabernet-Sauvignon and Sauvignon blanc (Carey *et al.*, 2008b).

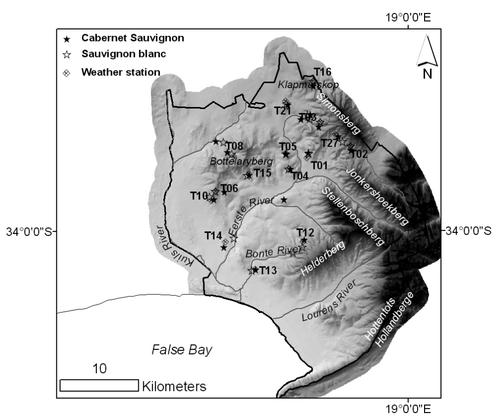

Figure 1 - The location of the Stellenbosch Wine of Origin District (solid black line) together with the positions of weather stations (labelled Tn) and experimental plots of *Vitis vinifera* L. cv. Cabernet-Sauvignon and Sauvignon blanc used in the data generation phase (Carey 2008b).

6. Identification of viticultural terroirs

Relationships between predictor environmental variables and variables for which digital data layers were available, had to be determined. The relationship between soil-related parameters and the soil or geology class of the plot, as determined from the digital data layers was investigated by means of one-way ANOVAs (Statistica 6.1, StatSoft, Inc., Tulsa, USA) with the soil or geology class as categorical predictor. As the Winkler Growing Degree-day Index was the only temperature related variable for which a digital data layer was available, it was correlated with the temperature related predictor variables (weather station data) and regressions were performed using the General Regression Model in Statistica 6.1. Environmental data layers were divided into classes for each viticultural and oenological variable based on the decision trees that had been determined (see Results and Discussion). Median class values were calculated for each natural terroir unit using the zonal statistics function of Spatial Analyst™ in ESRI®ArcMap™ 8.2.

7. Significance of identified terroir units for viticulture

A map of vineyards, that was compiled from a classification of Landsat TM images (Capture date 23 November, 2001), was obtained from the Geoinformatics Division of ARC Institute for Soil, Climate and Water. This map was used to determine the area of each terroir unit that was planted to grapevines in 2001.

RESULTS AND DISCUSSION

1. Determination of rules for the identification of viticultural terroirs for Cabernet-Sauvignon

From the regression tree analyses discussed in detail in Carey *et al.* (2008b), it appeared that the potassium content of the subsoil affected the performance of Cabernet-Sauvignon in the Stellenbosch Wine of Origin district. Sandstone soils are expected to have the lowest total soil potassium content, followed by shale derived soils and finally granite derived soils (Wooldridge, 1988). Following this evidence, vineyards on soils derived from sandstone would be expected to produce wines with a lower wine pH, specific gravity and extract. Vineyards on shale derived soils would be expected to ripen fully. Vineyards on granite derived soils, on the other hand, would be expected to produce wines with a higher pH, specific gravity and extract. Statistical analyses of the soil

Table 1 - Regression based algorithms that were used to determine climatic variables from the automatic weather station network in the Stellenbosch Wine of Origin District (F. Knight, Agri Informatics, unpublished data, 2004).

Variable	Algorithm
Rain $_{Growing\ season}$	(1/Solar radiation$_{315,15}$)^2 x (0.3 x altitude +200)
Rain $_{February}$	0.6 x Rain $_{Growing\ season}$
Rain $_{March}$	0.7 x Rain $_{Growing\ season}$
Rain $_{October}$	0.19 x Rain $_{Growing\ season}$
Rain $_{November}$	0.18 x Rain $_{Growing\ season}$
Rain$_{mbh}$ – Cabernet-Sauvignon	(14/28 x Rain $_{February}$) + (14/31 x Rain $_{March}$)
Radiation$_{mbh}$ – Cabernet-Sauvignon	Solar Analyst run on 28 February
Radiation$_{mbh}$ – Sauvignon blanc	Solar Analyst run on 6 February
Winkler Growing degree-day Index	-0.7614 x Altitude + 2016.8
Evapotranspiration$_{mbh}$	-0.0596 x Altitude + 169.11
Wind exposure	Sum of (Solar radiation W,SW,S,SE)/4

mbh = month before harvest

data from the experimental plots indicated, however, that the potassium content of the sub-soil did not differ significantly between soils associated with rocks of the Tygerberg Formation, granite, and the weathering products of Malmesbury rocks and granite, or between residual soils, red and yellow apedal to neocutanic soils and medium-deep wet duplex soils (data not shown). Sandy soils and soils derived from sandstone could not be included in the analysis due to lack of representation. This lack of an expected relationship was substantiated by Conradie *et al.* (2002), who found that potassium levels of lower soil horizons in the Stellenbosch area could not be related to underlying geological formations, probably as a result of management practices, especially mineral fertilization (vid. Seguin, 1986). Amelioration prior to planting and annual fertilisation would be expected to dramatically influence the potassium contents of medium textured soils. It is, however, known that sandy soils (<10 % clay) in the South Western Cape have generally low potassium contents and that potassium leaches rapidly from these soils (Conradie, 1994). It was, therefore, assumed that sandy soils (well and poorly-drained alluvial soils, excessively drained sandy soils and shallow dry sands), together with sandstone or scree (predominantly of sandstone origin, Theron *et al.*, 1992) related soils would have the lowest potassium contents.

Soil clay content and S-value had been determined as predictor variables for fullness on mouth-feel. Neither of these variables was available from the existing digital soil data. However, all the plots classified in the node with low clay content were associated with granite of the Kuils River-Helderberg Pluton. Although the granite of the two plutons were not separated by means of their description within the digital geological data, the Kuils River - Helderberg Pluton fell predominantly within the extent of the sea breeze and could therefore be distinguished on a natural terroir unit level. Sandy soils, together with sandstone or scree related soils, were also included in this class as the associated soils were assumed to have low clay content. Although the S-value did not differ significantly with soil or geology class, medium-deep wet duplex soils had a lower mean S-value than residual or well-drained structureless soils. Although soil water availability was not determined, the above arguments may reflect the effects of altered soil water status and availability on grapevine functioning and wine style as geological parent material, soil texture and base status can be related to soil water availability. This aspect deserves further study in this region.

Climate also appeared to have an influence on the must composition and aroma characteristics of Cabernet-Sauvignon. Evapotranspiration was related to must composition, possibly via temperature and wind related effects (Carey *et al.*, 2008b). Various temperature variables were used as predictors for wine attributes, but they were all significantly correlated with the Winkler Growing Degree-day Index (table 2) and could, therefore, be replaced with this index.

The models used to determine the aptitude of the natural terroir units with respect to the various viticultural and oenological parameters of Cabernet-Sauvignon, are given in table 3.

2. Terroir units for Cabernet-Sauvignon

Eighty-two viticultural terroirs for Cabernet-Sauvignon production were delimited in the Stellenbosch Wine of Origin District. Sixty-two of these terroirs are represented within the area planted to grapevines in 2001. The predicted response of Cabernet-Sauvignon to these terroirs varied between the following two extremes: terroir 1 -

Table 2 - Correlation coefficients of temperature variables with the Winkler Growing Degree-day Index for Cabernet-Sauvignon in Stellenbosch, South Africa.

Variable	R	R^2	N	$p \leq 0.0001$
Mean maximum temperature (month before harvest)[1]	0.62	0.38	85	***
Mean minimum temperature (month before harvest)	0.61	0.37	94	***
Mean maximum temperature (October, November)	0.87	0.75	85	***
Mean temperature (October, November)	0.85	0.63	85	***

[1]The mean date of harvest for the seven-year period was used, i.e.14 March

Table 3 - Viticultural and oenological variables and their categories used in the determination of viticultural terroirs for the production of Cabernet-Sauvignon in Stellenbosch, South Africa.

Variable	Class	Environmental variable	Expected response
Yield per meter cordon	1	Altitude ≤147 m	>1.7 kg for all clones
	2	Altitude 147.1 m - 181 m	1.1-1.8 kg depending on clone
	3	Altitude >182 m	< 1.8 kg for all clones
Must composition	1	Evaporation_{mbh} ≤149 mm	Must TTA ~ 8.9 g/L Must pH ~ 3.2 Maturity Index ~ 25
	2	Evaporation_{mbh} 149.1 mm - 156 mm	Must TTA ~ 7.5 g/L Must pH ~ 3.2 Maturity Index ~ 31
	3	Evaporation_{mbh} >156 mm	Must TTA ~ 7.5 g/L Must pH ~ 3.5 Maturity Index ~ 31
Wine Specific gravity	1	Altitude ≤ 289 m; Geology = scree, sandstone or Soil = sandy	~0.9950 g/cm^3
	2	Altitude ≤ 289 m, Other soils	~0.9958 g/cm^3
	3	Altitude > 289 m	~0.9940 g/cm^3
Wine extract	1	Geology = scree, sandstone or Soil = sandy	Extract <30 g/L
	2	Other	Extract >30 g/L
Wine pH	1	Altitude ≤285 m, Geology = scree, sandstone or Soil = sandy	~3.8
	2	Altitude ≤285 , Other soils	~3.9
	3	Altitude >285 m	~3.6
Wine total titratable acidity	1	Winkler GDD ≤1869	~7.3 g/L
	2	Winkler GDD >1869	~6.2 g/L
Fullness on mouth-feel[1]	1	Geology = scree, sandstone, granite (Kuilsriver-Helderberg Pluton) or Soil = sandy and Winkler GDD ≤1846	~5
	2	Geology and Soil = other and Winkler GDD ≤1846	~4.4
	3	Soil =wet duplex soils	~5.1
	4	Soil = Residual or freely drained, structureless soils	~5.6
Berry aroma[1]	1	Rain_{mbh} ≤36.5 mm, Winkler GDD ≤1832	~3.3
	2	Rain_{mbh} ≤36.5 mm, Winkler GDD >1832	~3.9
Spicy aroma[1]	1	$\text{Rain}_{Oct,Nov}$ ≤42.5 mm	~1.4
	2	$\text{Rain}_{Oct,Nov}$ 42.6 mm - 60.5 mm	~2.0
	3	$\text{Rain}_{Oct,Nov}$ >60.5 mm	~0.7
Floral aroma[1]	1	$\text{Rain}_{Oct,Nov}$ ≤80 mm; Winkler GDD ≤1616	~1.1
	2	$\text{Rain}_{Oct,Nov}$ ≤80 mm; Winkler GDD >1616	~0.7
	3	$\text{Rain}_{Oct,Nov}$ >80 mm; Winkler GDD ≤1753	~0.3
	4	$\text{Rain}_{Oct,Nov}$ >80 mm; Winkler GDD >1753	~0.6

mbh = month before harvest

[1]Sensory score on a 10-point scale

high yielding (>1.7 kg/m cordon), lower must acidity (ca. 7.5 g/L) and higher must pH (ca. 3.5) and maturity index (ca. 31), wine extract lower than 30 g/L, high wine pH (ca. 3.8), low wine acidity (ca. 6.2 g/L), not very full on mouth-feel, and a wine aroma with slightly more intense berry notes and less spiciness; and terroir 32 - Low yielding (<1.8 kg/m cordon), higher must acidity (ca. 8.9 g/L), lower must pH (ca. 3.2) and maturity index (ca. 25), wine extract higher than 30 g/L, lower wine pH (ca. 3.6), higher wine acidity (ca. 7.3 g/L), full on mouth-feel, less intense berry aromas and more intense spicy and floral aromas. Cabernet-Sauvignon in Stellenbosch is expected to yield between 2 kg/m and 4 kg/m cordon, attain an average must total titratable acidity of between 6.6 g/L and 7.1 g/L and a maturity index in a range between 31 and 36 (Goussard, 2008). A wine pH above 3.6 is undesirable. A wide range of aromas such as berry, eucalyptus, raspberry, grassy, green pepper, mint, nut and olive have been described (Goussard, 2009). In general, the berry and fresh vegetative notes are expected to dominate.

These two extremes were not well represented in the Stellenbosch Wine of Origin District. Terroir 1 represented only 19 ha of coastal sandy soils on mid- to footslope positions with a north-westerly aspect. Terroir 32 represented 205 ha of pockets of granite-derived soils on high-lying north westerly upper midslope positions.

The terroirs with the largest surface areas for the potential production of Cabernet-Sauvignon in the Stellenbosch Wine of Origin were terroirs 2 (14 248 ha) and 9 (9,799 ha). Very few vineyards were planted on terroir 2, which consisted predominantly of alluvial and Aeolian sand soils at low altitudes. This unit has a similar predicted response as terroir 1, with the only difference being in the predicted intensity of floral notes. Terroir 9 was represented by wet duplex soils at altitudes below 200 m on varying expositions. This unit was predicted to result in vineyards with the following characteristics: high yielding (>1.7 kg/m cordon), lower must acidity (ca. 7.5 g/L) and higher must pH (ca. 3.5) and maturity index (ca. 31), wine extract higher than 30 g/L, high wine pH (ca. 3.9), low wine acidity (ca. 6.2 g/L), fairly full on mouth-feel, and a wine aroma with slightly more intense berry notes and less spiciness

The terroir units having the greatest area planted to vineyards were terroirs 9, 17 and 54 (for descriptions, refer to tables 4 and 5). It is world-wide phenomenon that, for easier mechanisation and thus easier/cheaper production, vineyards were increasingly planted on flatter areas in the past. In the Stellenbosch Wine of Origin District, these areas are represented by terroirs 9 and 17. On the other hand, hillside vineyards have long been recognised for quality wine production, in this case represented by terroir 54.

3. Determination of rules for the identification of viticultural terroirs for Sauvignon blanc

From the regression tree analyses performed in a first stage of this study (Carey *et al.*, 2008b), it appears that the performance of Sauvignon blanc is predominantly related to soil texture, wind exposure and temperature, both during the green berry growth stage and the month prior to ripening.

The yield to pruning mass ratio and wine specific gravity and, to a lesser extent, pruning mass and maturity index (Maturity index = (must soluble solids x 10)/must

Table 4 - The 10 dominant terroir units for Cabernet-Sauvignon based on vineyard plantings in 2001.

(Classes for the viticultural and oenological variables must be interpreted together with table 3.)

Terroir	Area (Ha)	Berry aroma	Extract	Floral	Fullness	Must composition	Spicy aroma	Wine pH	Wine TTA	Yield
9	2494	2	2	4	3	3	3	2	2	1
15	177	2	2	2	2	3	3	2	2	2
16	446	2	2	4	2	3	3	2	2	2
17	1674	2	2	4	3	3	3	2	2	2
35	334	1	2	4	4	1	3	3	1	3
48	206	1	2	4	1	2	3	2	1	3
50	189	2	2	4	1	2	3	2	1	3
54	780	1	2	4	4	2	3	2	1	3
55	226	2	2	2	4	2	3	2	1	3
74	234	2	2	4	3	3	3	2	1	3

Table 5 - The environmental characteristics of dominant terroir units for Cabernet-Sauvignon.

Terroir	Environmental characteristics
9	Lower-lying (<200 m above sea-level) lower mid-slope to valley bottom positions with wet duplex soils.
15	North-westerly upper mid-slope positions between 100 m and 200 m altitude, with residual to structureless soils of granite (Kuils River – Helderberg Pluton) origin and within the extent of the sea breeze influence.
16	South-westerly and easterly mid-slope positions between 100 m and 200 m altitude, with soils of granite (Kuils River – Helderberg Pluton) origin and within the extent of the sea breeze influence.
17	Wet duplex soils between 100 m and 200 m altitude, outside the extent of the sea breeze influence on varying expositions. Predominantly the northern part of the Stellenbosch Wine of Origin District, between the Bottelaryberg and Simonsberg
35	Residual or structureless soils between 300 m and 400 m altitude on mid-slope positions on the flanks of the mountains.
48	Residual or structureless soils of granite (Kuils River – Helderberg Pluton) origin between 200 m and 300 m above sea-level. Predominantly on easterly slopes on the Bottelaryberg.
50	Residual or structureless soils of granite (Kuils River – Helderberg Pluton) origin between 200 m and 300 m altitude. Predominantly on south-westerly slopes on Helderberg, Hottentots Holland mountains and Bottelaryberg.
54	Residual, dry duplex, or structureless soils between 200 m and 300 m altitude on the flanks of the mountains.
55	North-westerly upper mid-slopes between 200 m and 300 m altitude with residual or structureless soils (predominantly originating from rocks of the Tygerberg formation).
74	Wet duplex soils between 200 m and 300 m altitude. Predominantly on the north-western flanks of the Simonsberg, similar position to Terroir 17.

Table 6 - Correlation coefficients of temperature variables with the Winkler Growing Degree-day Index for Sauvignon blanc.

Variable	R	R^2	N	$p \leq 0.0001$
Mean minimum temperature$_{mbh}$[1]	0.66	0.30	82	***
Mean maximum temperature (October, November)	0.87	0.75	82	***
Mean minimum temperature (October, November)	0.62	0.38	82	***
Mean temperature (October, November)	0.84	0.63	82	***

[1] mbh = month before harvest. The mean date of harvest for the seven-year period was used (20 February)

titratable acidity), were related to the clay content of the lower horizons of the soil. It appeared from comparison of the subsoil clay content (depth-weighted mean between 35 cm and 70 cm) of the Sauvignon blanc reference plots and the digital soil and geological data, that soils associated with quaternary weathering products of Malmesbury rocks could be expected to have high clay contents (>34 %) in the lower soil horizons.

Wind exposure was related to both the yield of the vine and the capacity or total dry matter production (estimated with the formula of Deloire *et al.*, 2002), with increased exposure to wind in the early part of the season being associated with higher yield. This is discussed in greater detail in a previous paper (Carey *et al.*, 2008b). Wind is one of the climatic variables with the greatest degree of spatial variation (Lebon, 1993; Carey, 2001) and as a result is not easy to model on a mesoclimatic scale. The digital data layer used was estimated from the mean solar radiation for the wind directions W, SW, S and SE (FH Knight, unpublished data, 2004), which are the dominant summer wind directions in the South Western Cape (Kendrew, 1961).

Sauvignon blanc is notably sensitive to temperature, and lower minimum temperatures during the month prior to ripening were associated with lower wine pH values. In addition lower minimum temperatures prior to véraison were associated with more intense bell-pepper and grassy aroma characteristics in the wines. Warmer sites and seasons were associated with a higher intensity of tropical fruit and spicy notes in the wines. All temperature related predictor variables were significantly correlated with the Winkler Growing Degree-day Index (table 6) and were therefore replaced with this index.

The models used to estimate the viticultural and oenological performance of Sauvignon blanc in the Stellenbosch Wine of Origin District are shown in table 7.

4. Terroir units for Sauvignon blanc

Two-hundred and thirty-five terroir units were identified for Sauvignon blanc wine production. Each of these terroir units can be considered to be homogenous with respect to the viticultural and oenological variables given in table 7. The response of Sauvignon blanc to the environment was more clearly distinguishable with the

Table 7 - Viticultural and oenological variables and their classes used in the determination of viticultural terroirs for the production of Sauvignon blanc in Stellenbosch, South Africa.

Variable	Class	Environmental variable	Expected response
Flowering date	1	Winkler GDD ≤1729	~24-Nov
	2	Winkler GDD 1729.1 - 1919	~09-Nov
	3	Winkler GDD >1919	~03-Nov
Harvest date	1	Winkler GDD ≤1729	~11-Mar
	2	Winkler GDD >1729, $Radiation_{mbh}$ ≤817	~23-Feb
	3	Winkler GDD >1729, $Radiation_{mbh}$ >817	~17-Feb
Yield per meter cordon	1	Wind exposure ≤67	~1.5 kg/m
	2	Wind exposure 67.1 - 68	~2.0 kg/m
	3	Wind exposure >68	~2.7 kg/m
Yield : pruning mass ratio	1	Distance from sea ≤8 km	~5.6
	2	Distance from sea >8 km, soils derived from weathering products of Malmesbury rocks	~2.1
	3	Distance from sea >8 km, other soils	~3.9
Capacity[1]	1	Wind exposure ≤65	~0.7 kg/m cordon
	2	Wind exposure 65 - 67	~0.8 kg/m cordon
	3	Wind exposure >67	>1.0 kg/m cordon
Wine specific gravity	1	Slope ≤3%	~0.9890 g/cm^3
	2	Slope >3%, soils derived from weathering products of Malmesbury rocks	~0.9906 g/cm^3
	3	Slope >3%, other soils	~0.9911 g/cm^3
Wine pH	1	Winkler GDD ≤1967	~3.6
	2	Winkler GDD >1967	~3.8
Fullness[2]	1	Winkler GDD ≤1777	~5.9
	2	Winkler GDD 1777 - 1929	~5.3
	3	Winkler GDD>1929	~5.0
Fresh vegetative aroma[2]	1	Winkler GDD ≤1910, other soils	~3.6
	2	Winkler GDD ≤1910, stony complexes of structureless and residual soils	~4.2
	3	Winkler GDD >1910	~2.9
Dried vegetative aroma[2]	1	Winkler GDD ≤1856	~0.8
	2	Winkler GDD >1856, distance from sea ≤14 km	~1.5
	3	Winkler GDD >1856, distance from sea >14 km	~1.1
Tropical fruit aroma[2]	1	Winkler GDD ≤1867, distance from sea ≤17 km	~1.6
	2	Winkler GDD ≤1867, distance from sea >17 km	~2.3
	3	1867< Winkler GDD ≤1944	~2.7
	4	Winkler GDD >1944	~3.3
Spicy aroma[2]	1	Winkler GDD ≤1844, $radiation_{mbh}$ ≤744	~0.2
	2	Winkler GDD ≤1844, $radiation_{mbh}$ >744	~0.4
	3	Winkler GDD >1844	~0.6

mbh = month before harvest
[1]Puissance or estimated total dry matter production: 0.5 x pruning mass + 0.2 x yield (Deloire et *al.*, 2002); [2]Sensory score on a 10-point scale

regression trees, resulting in the inclusion of more environmental variables for the determination of terroir units. This, together with less overlap between the environmental variables, resulted mathematically in a greater number of terroir units.

The two extremes were terroir 1 and terroir 233. Terroir 1 represented sites with potentially a late phenological cycle, low yield (ca. 1.5 kg/m cordon), high yield: pruning mass ratio (ca. 5.6), low total dry mass production (ca. 0.7 kg/m cordon), wine specific gravity of ca. 0.9911 g/cm^3, lower wine pH (ca. 3.6), wines that were fuller on mouth-feel, with moderate fresh vegetative aroma characteristics (bell pepper, grassy) and less intense dried vegetative (tea, tobacco) and tropical fruit aromas. This terroir was represented by high-lying (>500 m above sea level) north-westerly slopes on the Helderberg and Hottentots Holland mountains. The soils were residual with quaternary sandstone (scree) origin. This terroir covers ca. 346 ha but had no vineyard plantings in 2001. Terroir 233 is potentially associated with an early flowering period and mid-ripening period, high yield (ca. 2.7 kg/m cordon), moderate yield: pruning mass ratio (ca. 3.9) and high total dry matter production (>1.0 kg/m cordon). The wines would be expected to have a specific gravity in the region of 0.9911 g/cm^3, pH values ca. 3.6, be potentially less full on mouth-feel and have more dominant tropical fruit and spicy aromas. This terroir is found on low-lying

Table 8 - The 10 dominant terroir units for Sauvignon blanc in Stellenbosch, South Africa, based on vineyard plantings in 2001.

(Classes for the selected viticultural and oenological variables must be interpreted together with table 7)

Terroir	Ha	Harvest	Yield	Capacity	Wine SG	Wine pH	Fullness	Fresh veg. aroma	Dried veg. aroma	Tropical fruit aroma
37	1223	2	1	1	3	1	2	1	2	3
38	708	2	1	1	3	1	2	3	2	3
105	493	2	3	3	3	1	2	1	1	1
108	1304	2	3	3	3	1	2	1	2	3
109	674	2	3	3	3	1	2	3	2	3
124	447	2	3	3	3	1	2	1	1	1
140	419	3	1	1	3	1	2	1	1	1
152	548	3	1	1	3	1	2	1	1	1
174	442	2	1	1	3	1	2	3	2	3
176	684	2	1	1	3	1	3	3	2	4

Table 9 - The environmental characteristics of dominant terroir units for Sauvignon blanc in Stellenbosch, South Africa.

Terroir	Environmental characteristics
37	North-westerly slopes between 100 m and 200 m altitude. The associated soils are expected to have a low to moderately-high clay content (≤34%) in the lower soil horizons
38	Similar to Terroir 37 but situated slightly closer to the coast
105	South-westerly slopes between 200 m and 400 m altitude. The associated soils are expected to have a low to moderately-high clay content (≤35%) in the lower soil horizons
108	South-westerly slopes between 100 m and 200 m altitude. The associated soils are expected to have a low to moderately-high clay content (≤35%) in the lower soil horizons
109	Similar to Terroir 108, but situated slightly closer to the coast
124	South-westerly slopes between 200 m and 400 m altitude. The associated soils are expected to have a low to moderately-high clay content (≤35%) in the lower soil horizons
140	North-westerly slopes between 200 m and 400 m altitude, predominantly on the Helderberg, Hottentots Holland mountains and the Bottelaryberg. The associated soils are expected to have a low to moderately-high clay content (≤35%) in the lower soil horizons
152	North-westerly slopes between 200 m and 400 m altitude. The associated soils are expected to have a low to moderately-high clay content (≤35%) in the lower soil horizons
174	North-westerly slopes between 100 m and 200 m altitude. The associated soils are predominantly duplex or alluvial in nature.
176	Low-lying (<100 m altitude) easterly and north-westerly slopes on the coastal plain and in the river valleys. The associated soils are expected to have a low to moderately-high clay content (≤35%) in the lower soil horizons

south-westerly foot-slopes in the Eerste River valley in the immediate environs of Stellenbosch town, and has duplex or well-drained deep alluvial soils. This terroir covered only ca. 40 ha and also had no vineyards cultivated in 2001.

Similarly to the terroirs for Cabernet-Sauvignon, the terroirs with the greatest surface area identified in the Stellenbosch Wine of Origin District for potential Sauvignon blanc production were the relatively flat coastal and valley sandy soils, but these were not planted to vineyards. One hundred and seventy-three of the terroir units were represented in the area cultivated under vineyards in 2001. The dominant terroir unit planted to vineyards was Terroir 108 (tables 8 and 9), which consisted predominantly of south-westerly slopes between 100 m and 200 m above sea level. The associated soils would be expected to have a low to moderately high clay content (≤34 %) in the lower soil horizons. The expected viticultural response would be mid-season flowering and harvest, high yield (ca. 2.7 kg/m cordon), high yield: pruning mass ratio (ca. 5.6) and high dry matter production (>1.0 kg/m cordon). The associated wines would be expected to have a high specific gravity (ca. 0.9911 g/cm^3) and lower pH (ca. 3.6), be moderately full on mouth-feel and have a fairly complex aroma. The area covered by this terroir totals 3 679 ha, with an estimated 1 304 ha planted to vineyards.

Sauvigon blanc in South Africa is expected to yield between ca. 3 kg/m and 5 kg/m cordon (Goussard, 2008), but in reality older vineyards have much lower yields, which in our experience are regularly less than 2.0 kg/m cordon. The average total titratable acidity is expected to attain values of 7 g/L to 9 g/L. Budburst is expected to occur at the beginning of September and harvest is early mid-season (middle of February) (Goussard, 2008). A terroir that would be expected to yield a Sauvignon blanc wine with a high quality (high intensity of fresh vegetative, tropical fruit and spicy aromas, full on mouth-feel, low wine pH), but at the same time bearing a crop in excess of 2.0 kg/m cordon, would be located on the south-westerly upper midslopes of the Stellenboschberg, between 100 m and 200 m above sea-level on soils with a fairly high stone content. With the existing data, an area of 17 ha was identified. South-western slopes are generally sought for the establishment of Sauvignon blanc vineyards in South Africa in order to ensure cooler ripening conditions. This is reflected by the dominance of Terroir 108, which represents south-westerly slopes below 200 m.

CONCLUSIONS

Point data from field studies on the reaction of the grapevine to its site environment demonstrated relationships for Cabernet-Sauvignon and Sauvignon blanc respectively. The use of regression tree methodology (CART analyses) enabled the definition of decision trees for spatialisation of this data. Each natural terroir unit could be evaluated with respect to its potential viticultural and oenological response and thus grouped to identify terroir units.

The two cultivars included in this study differed in their response to the environment, although both responded to soil, geology and climate related variables, thus the full complex of terroir factors. Many more terroir units were determined for Sauvignon blanc than for Cabernet-Sauvignon, but this was probably due to the more distinct environmental response of Sauvignon blanc as compared to Cabernet-Sauvignon and thus the inclusion of more viticultural and oenological variables in the model for determination of viticultural terroirs. The relationship of Cabernet-Sauvignon with site environment was not always sufficiently clear to construct reliable decision trees and this limited the number of viticultural and oenological variables that could be included in the determination of the viticultural terroirs. This may have been due to the better adaptability of Cabernet-Sauvignon to diverse, and warmer, environments than Sauvignon blanc, but may also have related to the choice of environmental, viticultural and oenological variables that were monitored not being as suited to Cabernet-Sauvignon.

The response of Cabernet-Sauvignon to the environment was closely related to the potassium content of the sub-soil. Despite the implication of parent material in this response, the potassium content of the sub-soil appeared to be strongly affected by the agricultural usage of the land; to such an extent that the expected effects of the parent material of the soil are no longer visible. Potassium fertilisation of the soil may, therefore, alter the aptitude of the terroir for Cabernet-Sauvignon wine production and deserves further study. The effects of potassium content cannot, however, be simplified into guidelines for fertilisation based on this relationship alone, as the crux of the terroir concept is the integration and interaction of its component parts. Due to the reliance of the modelled Winkler Growing Degree-days and evapotranspiration on altitude, the main predictors of Cabernet-Sauvignon performance in the Stellenbosch Wine of Origin District were altitude and soil type and origin.

The must composition of Sauvignon blanc (total soluble solids, must pH and must total titratable acidity) was not significantly related to any environmental parameters and it can therefore be assumed that no site had an inability to ripen Sauvignon blanc. With respect to other viticultural and oenological parameters, the interaction of Sauvignon blanc with the environment was more clear. The expected temperature response of the aroma profile and wine acidity parameters was once again shown and used in the determination of viticultural terroirs. Exposure to wind was also an important variable, but was not easily modelled due to its high degree of spatial variability and deserves further study.

One of the main problems with GIS modelling, is the quality of the base data, such as lack of data, gaps in data coverage or the accuracy of the data being insufficient to answer questions. In this study, digital environmental data also proved to be one of the major constraining factors.

For many of the South African wine producing areas, spatial environmental data is limited. For Stellenbosch, however, there are more soil data available (1:50 000 peri-urban soil survey) as well as an automatic weather station network and more detailed environmental data is thus available. One of the dominant characteristics of Stellenbosch is its diversity of viticultural environments resulting from the ancient geological history, complex topography and proximity to the ocean and, although more detailed than many other regions, even this data may not fully represent the full range of terroirs present in this region. Although soil data was available at a suitable scale, it did not contain sufficient information and relevant soil characteristics had to be inferred per soil type based on known relationships or relationships estimated statistically with analytical data from the experimental plots. Digital geological data was not available at a suitable scale and only broad geological descriptions could be included. Similarly, despite the presence of an automatic weather station network, modelling of climatic data on a meso-scale holds challenges that could not be met within the confines of this study. These data « problems » limited the spatialisation of the viticultural and oenological response of Cabernet-Sauvignon and Sauvignon blanc in the Stellenbosch Wine of Origin District. This together with the fact that individual « terroirs » could reach the extent of more than 14 000 ha (terroir 2 for Cabernet-Sauvignon) cause us to question the use of the term « terroir » for this study. In this case the use of a less specific term, such as "zones of viticulture potential" may better reflect the results.

With this methodology it was possible to extrapolate point data from vineyard measurements to other areas, where vineyards have not yet been planted or their performance monitored. This is of value for the determination of potential before the establishment of new vineyards as well as the delineation of geographic indications. The use of data and knowledge garnered during a terroir investigation makes it easier to understand the environmental and social structure of a wine-producing region, thus facilitating the delimitation of districts (« regional » level). The identification of terroirs for production of specific cultivars, with their associated wine styles means that it is possible to base delimitation on a ward or « communal » level on expected wine characteristics. This should, to a certain extent, ensure a certain level of homogeneity of product linked to a geographical place name. At the level of research, this modelling has helped us to identify grapevine x environment interactions for further studies in greater detail.

Although the identified terroir units can only be considered preliminary, the methodology used has promising implications for different scales of study. Once the site specific decision trees have been constructed for the viticultural and oenological response of a cultivar, the spatialisation of the data should depend solely on the environmental data coverage, in particular the availability, resolution and accuracy of this data. Decision trees, therefore, have the potential to be applied from farm level to district scale for the identification of viticultural terroirs. It must however be remembered that as the scale becomes larger (more detailed), so the input data needs to become more reliable and measured, instead of extrapolated, and thus more measurement points will be required for input data. However, no matter the number od measurements, becayes such measurements are always point data, there is always a need for a certain extent of extrapolation.

Acknowledgements: This publication is based on research that was financially supported by the Agricultural Research Council, University of Stellenbosch, Winetech and the National Research Foundation under grant number 2053059. 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 Dr Martin Kidd for statistical analyses; A Schmidt and JCD Theron for technical assistance and Francois Knight, Ryk Taljaard, Dalene Opperman and Mike Wallace for assistance with the creation of digital data layers.

REFERENCES

Breiman L., Friedman J.H., Olshen R.A. and Stone C.J., 1984. *Classification and regression trees*. Chapman and Hall, New York.

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

Carey V.A., Saayman D., Archer E., Barbeau G. and Wallace M., 2008a. Viticultural terroirs in Stellenbosch, South Africa. I. The identification of natural terroir units. *J. Int. Sci. Vigne Vin*, **42**, 4, 169-183.

Carey V.A., Barbeau G., Archer E, and Saayman D., 2008b. Viticultural terroirs in Stellenbosch, South Africa. II. The interaction of Cabernet-Sauvignon and Sauvignon blanc with environment. *J. Int. Sci. Vigne Vin,* **42**, 4, 185--201.

Conradie W.J., 1994. Vineyard fertilization. [Title in Afrikaans: Wingerdbemesting]. *In: Working session on vineyard fertilization, Stellenbosch*. ARC Infruitec-Nietvoorbij, Stellenbosch.

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*., **3**, 62-71.

Deloire A., Lopez F. and Carbonneau A., 2002. Réponses de la vigne et terroirs. Éléments pour une méthode d'étude. *Progrès Agric. Vitic*., **119**, 78-86.

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.

Dubos J., 1984. Importance du terroir comme facteur de différenciation qualitative des vins. *Bull. OIV*., **639**, 420-434.

Ellis F. and Schloms B., 1975. *Reconnaissance 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. *Reconnaissance soil 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.

Goussard P.G., 2009. *Grape cultivars for wine production in South Africa.* Cheviot publishing, Green Point (*In press*).

Kendrew W.G., 1961. *The Climates of the Continents 5th Edition*. Oxford University Press, Oxford.

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.

Lebon E., 1993. De l'influence des facteurs pédo- et mésoclimatiques sur le comportement de la vigne et les caractéristiques du raisin. Application à l'établissement de critères de zonage des potentialités qualitatives en vignoble septentrional (Alsace). *PhD Thesis*, University of Burgundy

Morlat R., 1989. Le terroir viticole : contribution à l'étude de sa caractérisation et de son influence sur les vins. Application aux vignobles rouges de moyenne Vallée de la Loire. P*hD Thesis*, University of Bordeaux II.

Morlat R. (coord.), 2001. *Terroirs viticoles : étude et valorisation*. Oenoplurimédia, Chaintré.

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.

Seguin G., 1986. « Terroirs » and pedology of wine growing. *Experientia*, **42**, 861-873.

Skidmore A.K., 2002. The taxonomy of environmental models in the spatial sciences. *In: Environmental modelling with GIS and remote sensing*, pp. 8-25. Ed. A. Skidmore, Taylor and Francis, London.

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.

Vaudour E., 2000. Zonage viticole d'envergure macro-régionale : démarche et mise en œuvre dans les Côtes-du-Rhône méridionales. *Progrès Agric. Vitic*., **117**, 1, 7-16.

Vaudour E., 2001. Diversité des notions de terroir: pour un concept de terroir opérationnel. *Rev. Œnol.*. **101**, 39-41.

Vaudour E., 2003. *Les terroir viticoles. Définitions, caractérisation et protection*. Dunod ed., Paris.

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