The use of viticultural and oenological performance of grapevines to identify terroirs: the example of Sauvignon blanc in Stellenbosch

Utilisation des performances viticoles et œnologiques des vignes pour identifier des terroirs : exemple du Sauvignon blanc à Stellenbosch

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Abstract: Identification and characterisation of terroirs depends on knowledge of environmental parameters, functioning of the grapevine and characteristics of the final product. A network of plots of Sauvignon blanc was delimited in commercial vineyards in proximity to weather stations at 20 localities and their viticultural and oenological response was monitored for a period of seven years. These experimental plots were further characterised with respect to climate, soil and topography. In order for this information to be of use within terroir zoning studies it had to be placed in a spatial context. This was achieved with the use of regression tree methodology, which determined the relative importance of the environmental and management related variables and regression trees for each dependent variable. A knowledge-driven model used the rules generated in the regression tree analyses to directly classify natural terroir units with respect to expected response of Sauvignon blanc in the Stellenbosch Wine of Origin District. The expected response of these terroir units was compared to data obtained from a separate network of Sauvignon blanc plots monitored during the 2005 harvest season.

Key words: Sauvignon blanc, terroir, climate, soil, GIS

Introduction

A terroir is 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 (Morlat, 2001). Because the terroir concept 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 will 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). 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, have a compatible spatial variability and be easily acquired in the field (Riou *et al*., 1995). 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, 2001). This paper describes and discusses the determination of the cultivar x terroir interaction and the use of a knowledge-driven deductive model to determine viticultural terroirs for the cultivation of Sauvignon blanc grapes for wine production in the Stellenbosch Wine of Origin District.

Materials and methodes

Study area and vineyard sites. The study was limited to the Stellenbosch Wine of Origin District, South Africa, situated at 34°S, 19°E. Twenty reference plots of Sauvignon blanc of ca. 30 vines per plot were delimited during 1995 in commercial vineyards for a study period of seven years. Vine density, scion clone, rootstock, vine spacing, canopy height and irrigation practices were noted. Geographic co-ordinates, altitude, aspect and slope inclination were determined from 1:10 000 ortho-photos (Chief Directorate: Surveys and Mapping). The approximate minimum distance from the False Bay coast was determined in ESRI®ArcMap™ 8.2 and noted as distance from the coast.

Viticultural and oenological measurements

All vines were pruned to the norm of 16 buds per meter cordon within a four-week period. For each of these plots the dates of budburst, flowering and berries harvest-ripe were recorded when 50% of the monitored vines had reached the said stage. Pruning mass per meter cordon for 10 vines was determined. The canopy was evaluated at harvest using a score card adapted from Smart and Robinson (1991) and the yield per meter cordon for 10 vines was determined. A random standard sample of five bunches was selected from amongst bunches that had been harvested per plot for microvinification. Bunch characteristics (number of berries per bunch, mass of 100 berries) were determined for these samples. Musts were microvinified according to standard procedures (ARC Infruitec-Nietvoorbij) and sensorially evaluated ca. six months after harvest according to appropriate aroma categories from the Wine Aroma Wheel (Noble *et al.*, 1987), using an unstructured line scale and an expert panel of between 12 and 14 judges. The wines were presented in one session. Standard must and wine analyses were performed in a commercial laboratory.

Soil measurements

Soil profiles at each plot were examined in 2000 and described using the South African taxonomic system (Soil Classification Working Group, 1991). Standard soil chemical and physical analyses were performed in a commercial laboratory. On examination of the soil profiles, it was noted that for most of the plots grapevine roots only colonised the ploughed portion of the soil, and the depth of soil preparation was therefore assumed to be the effective soil depth.

Climatic measurements

A network of automatic weather stations (MCSystems) was established in 1995. Five of these weather stations were microclimatic and situated in the vineyard row while the remaining 11 were mesoclimatic and situated on open ground in the vicinity of vineyards. Data from mechanical weather stations (Agromet, ARC-ISCW) were used where available to complete the data set. The temperature sensors were housed in a Stevenson screen 1.2 m above the soil surface. The anemometer and pyranometer were situated at 2 m above the soil surface. Hourly climatic data were used to calculate a number of climatic variables (Appendix A).

Determination of the response of Sauvignon blanc to the site environment

Regression tree analyses (Breiman *et al.*, 1984) were used to analyse the complete data set. A variable importance factor in terms of its effect on the response variable was derived once the tree was built. This variable importance was calculated based on the number of times the variable was used as splitting variable and how well it separated low values from high values (M Kidd, personal communication, 2004).

Digital data

A 50 m Digital Elevation Model (DEM) was used to determine elevation and slope inclination using Spatial AnalystTM in ESRI®ArcMapTM 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. Spatial climatic interpolations from a seven-year series of data from the automatic weather station network were obtained (F Knight, Agri Informatics, unpublished data, 2004).

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 are described in detail in Carey (2005).

Identification of viticultural terroirs

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.

Significance of identified terroir units for viticulture

A map of vineyards (90% probability) was compiled from a classification of Landsat TM images (Capture date 23 November 2001) (JPA Van der Merwe, unpublished data, 2003). This map was used to determine the area of each terroir unit that was planted to grapevines in 2001.

Validation of terroir units with vineyard data

Three plots of 10 vines each were identified in selected commercial vineyards of Sauvignon blanc using remote sensing as a tool to identify homogenous plots where possible. Similar measurements to those previously described were made. Plots were harvested and microvinified. Sensory analyses of the Sauvignon blanc wines were performed ca. 9 months after harvest using a generic descriptive analysis. A panel was trained using a combination of the ballot and consensus methods during 5 sessions. An unstructured line scale was used. Twelve wines were presented in a session. Each panel member tasted each wine in duplicate. The experimental layout was that of a carry-over Latin Square.

Results and discussion

Parameters affecting the performance of Sauvignon blanc

The relative importance of the four most important environments or management related variables are given for each dependent variable in table 1. Only « independent »” variables with a relative importance of greater than 70% were considered to have any real importance in determining the dependent variable, unless they had a very narrow confidence interval (M. Kidd, personal communication, 2004).

Determination of rules for the identification of viticultural terroirs

The yield to pruning mass ratio (fig. 1a) and wine specific gravity (fig. 1b) and, to a lesser extent, pruning mass and maturity index (MustTSS x 10)/MustTTA), 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 affected both the yield of the vine (fig. 1c) and the capacity or total dry matter production (estimated with the formula of Deloire *et al.*, 2002) (fig. 1d), with increased exposure to wind in the early part of the season being associated with higher yield. Wind is one of the climatic variables with the greatest degree of spatial variation (Dumas *et al.*, 1997) 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.

Sauvignon blanc is notably sensitive to temperature, and lower minimum temperatures during the month prior to ripening were associated with lower wine pH values (fig. 1e). In addition lower minimum temperatures prior to véraison were associated with more intense bell pepper and grassy aroma characteristics in the wines (fig. 1f). Warmer sites and seasons were associated with a higher intensity of tropical fruit (fig. 1g) and spicy notes in the wines. All temperature related predictor variables were significantly correlated with the Winkler Growing Degree-day Index (table 2) and were therefore 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 Sauvignon blanc, are given in table 3.

Table 1 - Relative importance of the four most important variables affecting the performance of Sauvignon blanc in the Stellenbosch Wine of Origin District, South Africa

Dependent variable	Environmental and management related variables (relative importance)
Phenology	
Date of flowering	**Flo_MaxT**[1] (97.3%), Flo_MeanT (96.9%), Winkler (75.2%), HI (67.9%)
Date of harvest	**Flo_MaxT** (90.7%), Flo_MeanT (89.6%), Winkler (60.8%), **Rad** (53.2%)
Growth and yield	
Yield (kg/m cordon)	**Flo_WSgr4** (82.3%), WS (68.8%), **WSgr4**(62.3%), Soil_prep (30.3%)
Bunch mass (g)	**Clone** (81.8%), **vine density** (39.4%), K Low (37.3%), soil_prep (33.7%)
Berry mass (g)	Flo_maxT (89.5%), **Flo_rain** (73.6%), **Flo_meanT** (70.5%), rad (65.1%)
Yield: pruning mass ratio	Slope (73.5%), **dist_sea** (62.8%), clay (62.6%), **clay_low** (55.2%)
Total estimated dry matter production[2]	**WSgr4** (79.9%), **vine density** (61.7%), **WS** (61.0%), Flo_WSgr4 (51.9%)
Must analyses	
pH	**Plow** (32.6%), S-val (31.1%), **dist_sea** (30.5%), Alt (28.1%)
Maturity index[3]	**Flo_rain** (47.1%), S-val (35.0%), rad (32.6%), **clay-low** (25.3%)
Wine analyses	
Specific gravity	**Slope** (59.8%), dist_sea (57.8%), **clay_low** (51.2%), alt (42.3%)
Alcohol (vol %)	**Rain** (60.6%), **SI** (40.0%), Flo_meanT (31.9%), Flo_maxT (30.6%)
Extract (g/L)	**Klow** (34.3%), **S-val** (32.2%), Tgr30 (30.3%), Silt (30.1%)
pH	**MinT** (62.0%), MeanT (44.9%), Silt (42.0%), plant-year (41.6%)
Total titratable acidity (g/L tartaric acid)	**MeanT** (73.7%), **GDD** (61.3%), **MinT** (55.7%), MaxT (48.5%)
Wine sensory analyses	
Acid	**Flo_minT*** (86.1%), Flo_meanT (82.4%), Flo_maxT (62.3%), **Tgr30** (35.8%)
Fullness	Flo_meanT (52.8%), **Flo_minT** (49.6%), **Flo_maxT** (44.3%), MeanT (43.3%)
Fresh vegetative	**Flo_minT** (76.8%), Flo_meanT (62.0%), Flo_maxT (53.3%), **Stone** (25.7%)
Cooked vegetative	Trellis system (44.2%), **Clone** 937.5%), **Alt** (28.4%), FiS (25.5%)
Dried vegetative	**Dist_sea** (51.1%), **Flo_meanT** (42.6%), Flo_rain (39.5%), Flo_MaxT (37.8%)
Tropical fruit	**Flo_meanT** (70.9%), **Flo_minT** (70.7%), Flo_maxT (58.0%), **dist_sea** (29.5%)
Spicy	**Flo_meanT** (79.5%), Flo_minT (70.6%), Flo_maxT (55.6%), **Rad** (29.5%)
Caramel	**Rain** (42.7%), Flo_minT (30.3%), **Flo_rain** (30.0%), Flo_meanT (29.6%)

[1]Bold type represents predictor variables selected for final regression trees [2]*puissance* (Deloire *et al.*, 2002) [3](MustTSS x 10)/MustTTA

Table 2 - Correlation coefficients of temperature variables with the Winkler Growing Degree-day Index

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]The mean date of harvest for the seven-year period was used, i.e.20 February

Terroir units for Sauvignon blanc

Two hundred and thirty-five terroir units were identified for Sauvignon blanc wine production in the Stellenbosch Wine of Origin District. One hundred and seventy-three of the terroir units were represented in the area cultivated under vineyards in 2001.

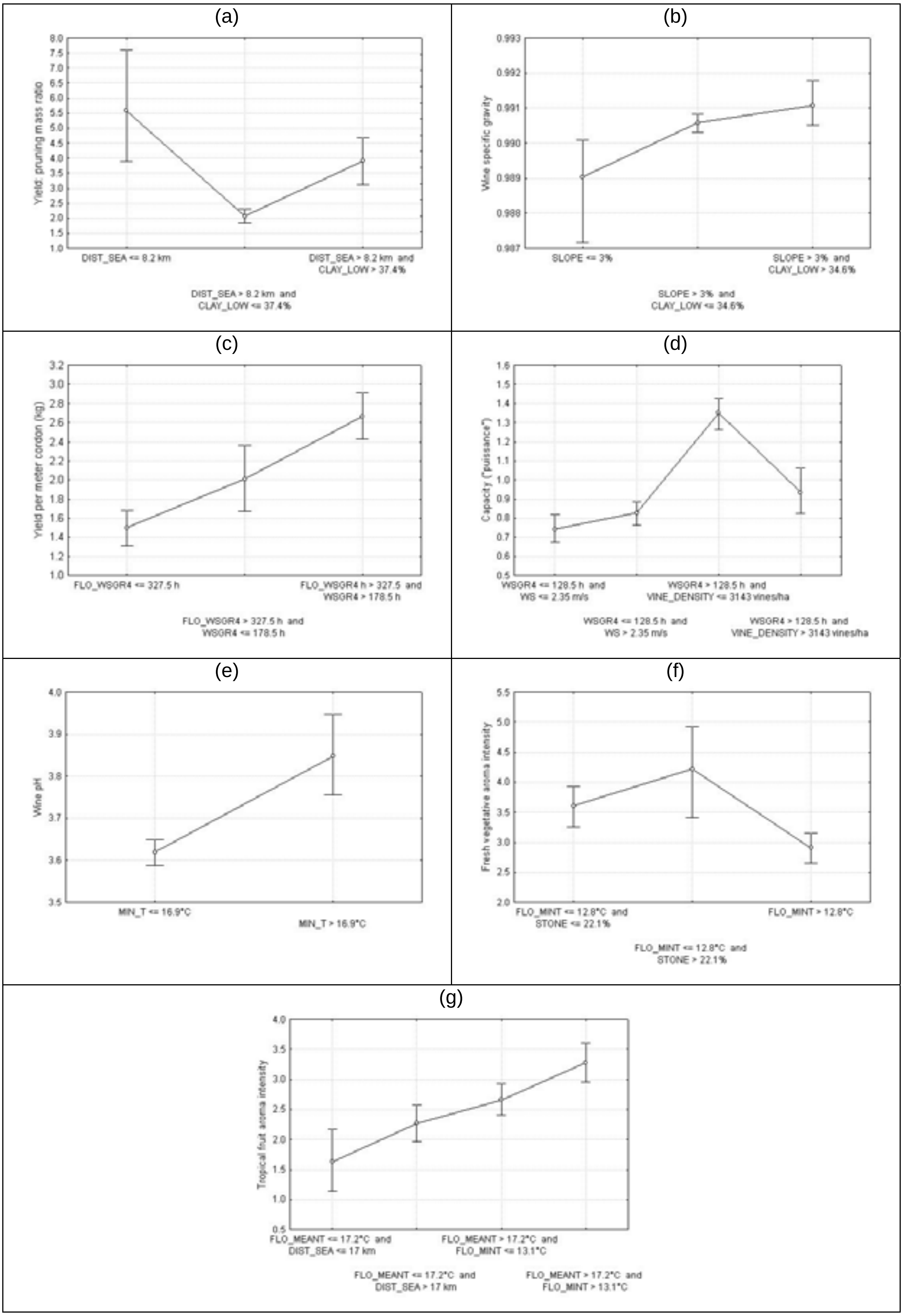

Figure 1 - Bootstrap mean values for terminal nodes of final regression trees of selected viticultural and oenological variables of Sauvignon blanc, Stellenbosch. Vertical bars denote 0.95 bootstrap confidence intervals.

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

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: 0.5xpruning mass + 0.2xyield (Deloire *et al.*, 2002)
[2]Sensory score on a 10-point scale

The terroir unit that was most represented in the area under vineyards was Terroir 108, which consisted of predominantly 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. 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 this terroir.

Validation of terroir units

The dates for flowering and harvest, although differing significantly between terroirs during the 2004/2005 season, did not correspond with the dates as predicted for the Sauvignon blanc terroirs. It has been shown in numerous studies that grapevine phenology is extremely sensitive to climatic variations. The predicted values were based on 7-year means and annual variation can thus be expected based on seasonal climatic fluctuations. Three (3) of 11 (27%) and five (5) of 11 (45%) cases for the yield:pruning mass ratio and capacity, respectively, were correctly predicted by the Sauvignon blanc terroirs. The yield per meter cordon was determined at harvest. Yield for Sauvignon blanc ranged between 1.0 kg and 4.3 kg per vine and was predicted successfully in eight (8) of 17 (47%) cases. Wine pH was successfully predicted in seven (6) out of 16 (38%) cases. It was less easy to compare the wine sensory analyses as different aroma categories were used, but for the categories green pepper and grassy, the wines for which the lowest scores for « fresh vegetative aroma characteristics » were expected were scored the lowest. Five temperature/relative humidity data loggers and 4 anemometers were placed in selected Sauvignon blanc vineyards during January in order to monitor the canopy microclimate. Vineyards where higher February and March temperatures were recorded produced wines in which tropical aromas dominated. Vineyards in which fairly cool February and March temperatures were recorded produced wines in which vegetative (green pepper and grassy) aromas dominated. Wine style appeared to be dependent on temperature. This corroborates the findings of the CART analyses for Sauvignon blanc. Further years of data are necessary in order to investigate the stability of these results.

Problems with data, such as lack of data, gaps in data coverage or the accuracy of the data being insufficient to answer questions, have been identified as one of the overriding problems associated with GIS modelling (Bregt *et al.*, 2002). In this study, digital environmental data also proved to be one of the major constraining factors. 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. 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. The modelled data that was used did not take the sea influence into account due to the paucity of weather stations in the coastal areas. Although RAMS analyses have been performed on a 200 m grid (Du Preez, Cautenet and Bonnardot, personal communication, 2004), this data is not yet available for a suitable period and it is not possible to perform these analyses at the grid scale of this study (50 m) for a large area.

Conclusions

Point data from field studies on the reaction of the grapevine to its site environment demonstrated relationships for Sauvignon blanc. The performance of Sauvignon blanc appeared to be related to soil texture, wind exposure and temperature, both during the green berry growth stage and the month prior to ripening. The clay content of the subsoil could be related to pruning mass, yield:pruning mass ratio and maturity index. Vineyards on soils with a high clay content in the subsoil can be associated with less vigorous growth but a less ideal must composition (total soluble solids and total titratable acidity). Contrary to expectation, increased exposure to wind in the early part of the season was associated with higher yield. Lower minimum temperatures during the month prior to ripening ensured lower wine pH values. 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 related to increased intensities of tropical fruit and spicy notes in the wines.

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 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 clearer. 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.

GIS data « problems » limited the spatialisation of the viticultural and oenological response of Sauvignon blanc in the Stellenbosch Wine of Origin District, and the accuracy of the extrapolation may in some cases be questionable. This was shown with the poor prediction of certain attributes for Sauvignon blanc on comparison of data generated from the new network with the expected characteristics of the delimited viticultural terroirs – especially those depending on climatic data.

Although these 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 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.

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References

BREGT AK, SKIDMORE AK and NIEUWENHUIS G, 2002. Environmental modelling: issues and discussion, 252-259. *In. Environmental modelling with GIS and remote sensing*. Ed. Skidmore A, Taylor & Francis, London.

BREIMAN L, FRIEDMAN JH, OLSHEN RA and STONE CJ, 1984. Classification and regression trees. Chapman & Hall, New York.

CAREY VA, 2005. The use of viticultural terroir units for demarcation of geographical indications for wine production in Stellenbosch and surrounds. *PhD Agric Thesis*, Stellenbosch University.

DELOIRE A, LOPEZ F and CARBONNEAU A, 2002. Réponses de la vigne et terroirs. Eléments pour une méthode d'étude. *Pr. Agric. Vitic.*, **119**, 78-86.

DUMAS V, LEBON E and MORLAT R, 1997. Différenciations mésoclimatiques au sein du vignoble Alsacien. *J. Int. Sci. Vigne Vin*, **31**, 1-9.

ELLIS F, RUDMAN R, SMITH-BAILLIE A, OOSTHUIZEN A and SCHLOMS B, 1976. 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 BHA, RUDMAN RB and OOSTHUIZEN AB, 1980. Grondassosiasie kaart van die Weskaap (Voorlopige kompilasie). Scale 1:250 000. Reg: No. 12042, SIRI, Department of Agriculture and Water Supply, Pretoria.

ELLIS F. and SCHLOMS B, 1975. Verkenningsgrondopname van die Eersterivieropvanggebied. Stellenbosch. Scale 1:25 000. Reg. No. 11296/1, SIRI, Department of Agricultural Technical Services, Pretoria.

MORLAT R (coord.), 2001. Terroirs viticoles: étude et valorisation. Oenoplurimédia, Chaintré, France.

NOBLE AC, ARNOLD J, BUECHSENSTEIN A, LEACH EJ, SCHMIDT JO and STERN PM, 1987. Modification of a standardized system of wine aroma terminology. *Am. J. Enol. Vitic.*, **38**, 143-146.

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.

SMART R & ROBINSON M, 1991. Sunlight into Wine. A handbook for winegrape canopy management. Winetitles, Adelaide.

SOIL CLASSIFICATION WORKING GROUP, 1991. Soil Classification. A Taxonomic System for South Africa. Memoirs on the Agricultural Natural Resources of South Africa No. 55. Department of Agricultural Development, Pretoria.

THERON JN, 1990. Geological Survey. 1:250 000 series. Sheet 3318 Cape Town. The Government Printer, Pretoria.

VAUDOUR E, 2001. Diversité des notions de terroir: pour un concept de terroir opérationnel. *Revue des Œnologues*. **101**, 39-41.

Appendix A : An explanation of the codes for environment and management related variables used in data analysis

Management related variables

Irrigate = Dryland or irrigated; **Rootstock** = name; **Clone** = scion clone, **Vine density** = Number of vines per hectare; **Canopy height** = Height between cordon wire and top wire; **Trellis system** = Type of trellis system; **Plant year** = year in which planted

Terrain related variables

Aspect = Compass directions in degrees; **Slope** = Slope inclination in %; **Altitude** = Height above sea level (m); **Dist_sea** = Minimum distance from the coast (km)

Climate related variables

Flo_maxT = Mean maximum temperature for October and November (°C); **Flo_minT** = Mean minimum temperature for October and November (°C); **Flo_meanT** = Mean temperature for October and November (°C); **Flo_rain** = Rainfall for October and November (mm); **Flo_WSgr4** = Number of hours with wind speed greater than 4 $m.s^{-1}$ for October and November (hrs); **MaxT** = Mean maximum temperature during the 31 days prior to harvest (°C); **MinT** = Mean minimum temperature during the 31 days prior to harvest (°C); **MeanT** = Mean temperature during the 31 days prior to harvest (°C); **GDD** = Total growing degree-days during the 31 days prior to harvest; **T2025** = Number of hours with a temperature between 20°C and 25°C during the 31 days prior to harvest; **Tgr30** = Number of hours with a temperature higher than 30°C during the 31 days prior to harvest; **Rad** = Total radiation during the 31 days prior to harvest; **Sun** = Total sunshine hours during the 31 days prior to harvest; **WS** = Mean wind speed during the 31 days prior to harvest (m/s); **WSgr4** = Number of hours with a wind speed greater than 4 m/s during the 31 days prior to harvest; **Evap** = Evaporation during the 31 days prior to harvest (mm); **Rain** = Rainfall during the 31 days prior to harvest (mm); **MinRH** = Minimum relative humidity during the 31 days prior to harvest (%); **MeanRH** = Mean relative humidity 31 days prior to harvest (%);**TVI** = Thermal variability index (Gladstones, 1992); **HI** = Huglin Index (Huglin, 1986); **Winkler** = Winkler Index (Le Roux, 1974); **DI** = Dryness Index (Tonietto and Carbonneau, 2004)

Soil related variables

Soil pH = Depth weighted mean of the subsoil l pH (0.3 m-1.0 m); **Stone** = Depth weighted mean of the % stones in the profile (0 m-1.0 m); **Plow** = Depth weighted mean of the subsoil phosphorous (mg/kg) (0.3 m-1.0 m); **Klow** = Depth weighted mean of the subsoil potassium (mg/kg) (0.3 m-1.0 m); **s-value** = Depth weighted mean of the S-Value (exchangeable cations) (cmol/kg) (0 m-1.0 m); **Clay_low** = Depth weighted mean of the subsoil clay content (%) (0.35 m-0.7 m) (Tesic, 2003); **Clay** = Depth weighted mean of the clay content (%) (0 m-1.0 m); **Silt** = Depth weighted mean of the silt content (%) (0 m-1.0 m); **FiS** = Depth weighted mean of the fine sand content (%) (0 m-1.0 m); **MeS** = Depth weighted mean of the medium sand content (%) (0 m-1.0 m); **CoS** = Depth weighted mean of the coarse sand content (%) (0 m-1.0 m); **Soilprep** = Observed depth of soil preparation; **SI** = Site index (Tesic, 2003)