CONTRIBUTION OF VERY HIGH RESOLUTION SATELLITE REMOTE SENSING TO THE MAPPING OF HARVEST ZONES IN THE MAIPO VALLEY (CHILE)

APPORT DE LA TELEDETECTION DE TRES HAUTE RESOLUTION SPATIALE A LA CARTOGRAPHIE DES ZONES DE VENDANGE DANS LA VALLEE DU MAIPO (CHILI)

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Key words: Satellite remote sensing, terroir, vine, diachrony

Abstract

Use of very high-resolution images, as a support to demarcating grape harvest zones, is recent in viticulture. Using very high resolution IKONOS (4 m-resolution) and supermode SPOT-5 (2.5 m-resolution) multispectral images, this paper here proposes an approach of segmentating a vineyard region into grape harvest zones. In addition to vine vegetation states, soil surface is characterized. This approach relies on a diachronic study at two significant dates of the vine cycle: March 2001 (IKONOS) and July 2002 (SPOT-5). The study is carried out over 134 ha, comprising 23 Cabernet-Sauvignon irrigated plots. Images are processed by successive maskings carried out on a Infrared Color (IRC) image, which alternately isolate vine vegetation or bare soils. The performing of Ascending Hierarchical Classifications result in defining 6 vine vegetation classes, which are ranked by chlorophyll biomass (and activity) qualitative level, and 4 bare soil classes. These results demonstrate that vine chlorophyll biomass qualitative levels are specifically related to some classes of bare soils. Results are discussed in relationship with viticultural data referring to variety, training system, row orientation, grass cover, irrigation, plant age, planting density.

Résumé

Les images de très haute résolution spatiale sont utilisées depuis peu en viticulture comme une aide à la cartographie des zones de vendanges. A partir d’images multispectrales de très haute résolution spatiale IKONOS (résolution 4 m) et SPOT-5 en supermode (résolution 2.5 m), on propose ici une démarche de segmentation d’une région de vignoble en zones de vendanges. Outre les états de la végétation de la vigne, on considère une caractérisation des états de surface du sol. La démarche repose sur une étude diachronique à deux dates sensibles du cycle de la vigne, mars 2001 (IKONOS) et juillet 2002 (SPOT-5). L’étude porte sur 134 ha, comprenant 23 parcelles irriguées de Cabernet-Sauvignon. Les traitements d’images consistent en des masquages, réalisés à partir d’une image infra-rouge couleur, qui isolent tour à tour la végétation de la vigne ou les sols nus. Des classifications ascendantes hiérarchiques conduisent à déterminer 6 classes de végétation de la vigne, ordonnées par niveau de biomasse (et d’activité) chlorophyllienne, et 4 classes de sols nus. Ces résultats montrent que le niveau de biomasse chlorophyllienne de la vigne est spécifiquement associé à certaines classes de sols nus. Les résultats sont discutés en liaison avec des informations viticoles concernant cépage, mode de conduite, orientation des rangs, enherbement, irrigation, âge des ceps, densité de plantation.

Introduction

Most studies based on satellite remote sensing techniques, and dealing with vineyards, vines and wines, are recent. Those using the earliest satellite sensors were carried out at coarse or intermediate spatial resolutions, with a pixel size much higher than a few meters. For instance, the 1-km resolution of NOAA-AVHRR thermal bands enabled prediction of surface temperature (Sandham and Zietsman, 1997; Santibañez et al., 1997), whereas the 20-m resolution SPOT multispectral images enabled to map vineyard soils and viticultural terroirs (Vaudour, 2001, 2003). Because of its discontinuous pattern, the vine cover itself is not so easy to study in remote sensing. Variations in either planting density, training system, row orientation, inter-row spacing, or inter-row management are likely to modify vine canopy as detected from space. Very high resolution sensors onboard post-1999 satellites open new prospects and applications for viticulture, with an enhanced spatial precision and the performing of detailed within-plot zoning. Recent research on detailed block zoning using aerial or satellite remote sensing focuses on the visible and near infrared spectral bands of the electromagnetic spectrum. Vineyard canopies have been monitored generally on the basis of the NDVI index (*Normalised Difference Vegetation Index*), which was put into relation with the LAI (*Leaf Area Index*), so as to estimate vine *vigour*, e.g. from 4 m-resolution IKONOS satellite images (Johnson, 2003; Johnson et al., 2003) and 25 cm-resolution aerial images (Hall et al., 2003). Vineyard soil surface variability was also investigated, e.g. from aerial photographs (Wassenaar et al., 2001). We here propose to analyze the spatial variability of both soil surface and vine vegetation, from a 2,5 m-supermode SPOT image and a 4 m-IKONOS image.

Materials and methods

Study area and approach

The study area is a commercial vineyard property of the Concha y Toro Winery, situated in the High Maipo Valley (Chile) and located at approximately 33°36'S/70°39'W. Climate is Mediterranean. Soils are fluvic skeletic cambisols developed on a quaternary fan terrace of the Maipo, less than 2 % slope. Study is focused on the sector planted with ungrafted Cabernet Sauvignon, which extends over 134 hectares subdivided into 23 plots.

The approach developed comprises 3 main steps:

1/ the first step consists in analyzing the various soils composing the studied sector, through a 2.5 m-resolution supermode SPOT5, dated 17 July 2002 (so-called “Soil image”);

2/ the second step consists in studying the remotely sensed vine spectral response, using a 4-m resolution IKONOS image, dated 17 March 2001 (so-called "Vine image");

3/ the final step consists in the diachronic study of both images, aiming at relying soil classes with distinct levels of the vine radiometric response. We will then determine modelled terroir units from a structural analysis of the “Vine image”.

Consistent interpretation of both images requires to analyze both human influence and viticultural data over the vine cycle. The viticultural data provided by the Winery describe plant variety, pruning system, planting year, row orientation, irrigation mode, irrigated water volumes, planting density and plant spacing, inter-row grass cover. There is no rootstock influence on vine functioning, because vine plants are ungrafted. Individual plants are adult and of unknown clonal origin (presumably multiclonal). Vinestocks age ranges from 10 to 23 years. Irrigation mode is either furrow irrigation or drip irrigation.

Processing and interpretation of the “Soil image”

Most works dealing with the concept of viticultural terroir emphasize the influence of soil (Seguin, 1970; Morlat, 1989; Van Leeuwen, 1991; Lebon, 1993; Dolédec, 1995; Vaudour, 2001). Within the framework of a viticultural zoning project, soils characterization can be carried out at various levels of complexity, according to the number of variables taken into account and according to wether they are spatialized or not (Vaudour, 2003). In this study, remote sensing data offer a compromise between both soil data availability, time and costs. Soils assessment by remote sensing makes it possible to obtain information on bare soil surfaces at several dates, continuously in geographical space and without deteriorating soil surface, while integrating many components such as: color, roughness, limestone content, total iron content, soil moisture (Escadafal, 1982). When the vineyard soils are dominantly bare in surface, which is the case at the beginning of Winter (“Soil image” of July), it can be expected to map the varied soils of the property, at the expected map scale of 1:10.000. For that purpose, an unsupervised ascending hierarchical classification (AHC) was implemented on the “Soil image”. The “Soil image” was corrected for geometric distorsion using 13 bench marks measured on the ground with a Differential Global Positioning System, of about 2 m geometrical error. A first geographical masking isolated the studied sector from the whole image. The masked infrared color

(IRC) image was visually interpreted. Then the available data on grass cover were used to mask grass-covered plots (with *Ray-grass* 1 row out of 2) in the remaining "Soil image", so as to perform processing on pixels of bare Cabernet-Sauvignon soils only.

Processing and interpretation of the "Vine image"

Vine-growers perceive distinct grape qualities according to the varied plots of the Property. In order to manage such variability each year, they divide the Property into 3 vine vigour levels, that they visually note as observed from the roadside separating two plots. In 2001, vine-growers estimated that 17 % of the studied area had low vine vigour, 61 % intermediate vine vigour and 22 % high vigour. With many observers, as it is the case of large farms, such notation is rather subjective and hardly repeatable. Conversely, there exist objective approaches on vineyards characterization, that are usually based on vine parameters measured in the field (Carbonneau, 2002; Deloire et al., 2002, 2004). Of all these parameters, vigour and potential exposed leaf area per m^2 or per hectare are particularly referred at, as having a significant effect on grape quality (Tisseyre *et al.*, 1999; Dry, 2000). Measurements are only local and numerous sampling expensive, and not easy to relate with satellite sensor spectral signal. Remote sensing assessment of vine growth parameters is however possible, provided consideration of other vegetation parameters, such as leaf area index (LAI). In California vineyards, Johnson et al. (2001) and Johnson (2003) demonstrated that LAI had significant relationship with multispectral radiometry for Cabernet Sauvignon, Cabernet Franc, Sauvignon Blanc, Merlot and Pinot Noir, notably through the Normalised Difference Vegetation Index (NDVI = near infrared – red/ near infrared + red). However, use of the NDVI raises several problems and should be used cautiously in view of its sensitivity to atmospheric effects and angular variations (Girard & Girard, 2003), as well as its highly sensitivity to both the whole canopy orientation angle (which may differ from a plot to another) and the distribution of horizontal and vertical leaves orientation angles in the vinestock. Thresholding of NDVI values is thus subjective, when field observations at the very moment of the imaging are not available and usable as bench marks, which is the case in this study. The NDVI was calculated and thresholded into 4 equipopulation classes, the spatial distribution of which revealed no interpretable organization in terms of viticultural management or soils.Vegetation monitoring supposes to easily interprete those values at each imaging date. Rather than the NDVI, we therefore proposed to perform multivariate classification of satellite data, in order to spatially assess vine vegetation behaviour. For that purpose, an unsupervised ascending hierarchical classification (AHC) was implemented on the "Vine image". As the principle of the AHC classifier is to classify all pixels, and as it is based on the fact that a pixel belongs to a group and only one, with a perfect separability between groups, the quality of the output image was not analyzed. The intra-class variability can however be significant, with several pixels misclassified (Girard & Girard, 2003). At the moment of the "Vine image" (Summer), vine foliage is significantly developed and close to the ripening. According to vine growers, Summer 2001 was characterized by a rather dry climate with no rainfall, consequently leaf removal has been negligible in 2001; however no precise data concerning shoot thinning are available. As all plants are adult, their total leaf area is expected to be of similar extent, though not measured in the field. Interpretation of vegetation chlorophyllian biomass levels is thus only qualitative. Chlorophyllian biomass ranges from very much chlorophyllian (+++) to chlorophyllian (+), then less chlorophyllian (-) to much less chlorophyllian (---). Plant spacing and irrigation are considered the most influent factors on this vine spectral response. The same geographical masking as that used for the "Soil image" of July 2002 enabled to isolate the Cabernet Sauvignon plots from their surroundings. In March, there is no grass cover in the vineyard, so vegetation is vine vegetation only. Through visual analysis of the IRC image, we intend to explore the chlorophyll biomass variability and control wether the channels observed in the "Soil image" correspond to distinct chlorophyllian biomass levels of the vineyard. After the visual analysis of the IRC image, a AHC was carried out on the image.

Diachronic analysis and determination of modelled terroir units

Diachrony is necessary in order for the segmentation into terroir units, since it enables to relate soil surfaces with vine status. Comparison between both processed "Soil image" and "Vine image" is focused on sectors with equivalent irrigation quantities and planting densities. In addition to diachronic analysis, the determination of terroir units here relies on a structural analysis performed on the result of classification of the "Vine image" (such image processing technique is also called “textural analysis”, however the term “texture” rather describes a set of pixels, each processed separately from the others). Structural analysis consists in classifying each pixel by taking account of the pixels in a defined neighbourhood and not on the only pixel taken separately as in the current methods of classifications previously used (Girard & Girard, 2003). It enables to better define the limits of the fuzzy spatial units and increase the compactness of the results obtained. The structural classifier OASIS (*Organisation et Analyse de la Structure des Informations Spatialisées,* organization and analysis of spatial data structure), requires to define reference patterns, the nuclei (Girard & Girard, 2003). The selected nuclei can be defined by several classes of objects, which lead to parametrize their composition vector. The entire image is gone through by a moving window, the size of which is chosen by the user depending on his objectives. Classification is then based on the calculation of the Manhattan distance from each pixel composition vector to each nucleus composition vector. The central pixel of each window is assigned to the nucleus located at the shortest distance. Using OASIS, we intend to produce a map that is readable and exploitable on the field, with a limited number of viticultural terroir units compatible with winery management. The vine-growers of the Property suggested to consider 6 final viticultural terroir units.

Results and discussion

1. Results

The property is crossed by dark, diagonal, nearly parallel and slightly curved alignments, which might correspond to former river channels diversions of the Maipo river, and coincide in the field to the low parts of slight concavities. These alignements are not visible in the 15-m resolution Aster IRC images (Parra et al., 2002). Brightest zones mainly correspond to 3 contiguous plots, the soil surface texture of which is clayey loam, and susceptible to sealing and compaction.

1.1 Bare soils

A first AHC classification was performed on the grass-cover-masked “Soil image”, assigning uncovered pixels to 32 classes. Some classes reveal a vegetation spectral behaviour in some places, owing to spontaneous-grown grass cover. After successive groupings of similar soil classes, distinction was finally made of 4 classes, among which 3 bare soils classes (Fig. 1). Of these 3 bare soils classes, the "dark soils" class coïncides with the diagonal former river channels crossing the Property, which correspond to wetter soils. The "rather dark soil" class mainly corresponds to zones situated outside the channels. The "bright soils" class is located in flat zones, where soils are interpreted as compacted. The only chlorophyllian zones consist in spontaneous grass, associated with the “rather dark soil” class and former channels, thus revealed as the most fertile sectors.

Crop cover plots

A second AHC classification was performed on the grass-covered part of the “Soil image”, assigning grass-cover pixels to 32 classes. After successive regroupings, distinction was finally made of 5 classes, among which 3 grass-cover classes and 2 bare soils classes. At the imaging date, grass chlorophyllian biomass extends over a total area of 42.8 ha, which corresponds to 52 % of the studied area only. This indicates varied phenological level of grass-cover growth according to the presence of more fertile soils. Both bare soils classes are dark, which is related to the 21-mm irrigation of corresponding plots in October and not to the soil itself or the beneficial fact that the crop cover has on the soil. Indeed, grass cover is usually employed in viticulture as a mean to fight against erosion on steeped slopes, improving soil structure (Morlat *et al.*, 1984; Dolédec *et al.*, 2003). Crop cover also influences vine vigour (Riou, 1997), but nutritive competition in surface layers is compensated within a few years (approximately 4-5 years) by a significant deep root development that is likely to provide the plant with water (Carsouille, 1997). From both the IRC image visual interpretation and the image classifications, active biomass coïncides with dark and wet soils.

1.2 Vine vegetation spectral behaviour

We only retain 6 classes starting from the 20 initial classes. These 6 classes will inevitably present misclassified or poorly classified pixels. Visual analysis of the IRC image leads to find the same spatial structures associated with the channels as previously for the dark and rather dark soils in the “Soil image”. These structures correspond to gradual intensities of dark red, which vary in the plots.

Whereas red-orange colors dominate in the South-Western part of the Property, brown red colors are present in the South-Eastern and Northern parts. Row orientation is observable in the image with a marked lining effect, which can be regarded as a noise with respect to the signal caused by soil surface variation. However, as planting width ranges from 1.8 m to 2.5 m, the 4-m resolution does not enable to isolate vine rows from bare soil inter-rows. The AHC is carried out in 32 classes, that, after statistical analysis of the varied spectral classes (notably the number of pixels per class), are grouped into 6 classes (Fig. 2), among which 2 main radiometric groups emerge:

1/ the "chlorophyllian biomass" classes, individualized by parallel pseudo-curves of their mean digital numbers (DN) values, with a significant slope between red/infrared, and rather low red values;

2/ the “low biomass” classes, characterized by elevated green and red DN values, as well as a significant red/infrared slope. These high green and red DN values reveal a significant mixture of bare soil.

The spatial analysis of the processed “Vine image” confirms that the channels are associated with very chlorophyllian and chlorophyllian vines. Plots without grass cover correspond to chlorophyllian vines. Plots revealing sol-vegetation mixels correspond to sealed soil surface (plots 31 and 32) or former pathways (plots 9 and 13).

1.3 Diachronic study and modelled terroir units

Figure 3 indicates the following described sectors with equivalent irrigation quantities and planting densities.

Sector 1: this sector is characterized by the oldest vinestocks of the Property (1979), a low planting density (2 000 plants/ha) and 50 mm furrow irrigated from February to March 2001. Rows are East-West oriented. A spatial organization of former river channels in diagonal shape is perceptible at the same locations in both images. These channels, which correspond to dark soils, give place to chlorophyllian or very chlorophyllian vines.

Sector 2: this sector is characterized by North-South oriented rows, 10 years-old vinestocks, 5 000 plants/ha and 100 mm irrigated from February to March 2001. Soils are dominantly bright in surface extending over 4.8 ha (88.8 % of the total bright soils area of the studied zone), mainly because of soil sealing due to furrow irrigation. They result in low chlorophyllian biomass in the processed “Vine image”. The presence of former river channels is restricted to the Northern part of this sector.

Sector 3: this sector is characterized by vinestocks aged 15-19 years, 4 000 plants/ha, ray-grass cover 1 row out of 2 between June and December and East-West oriented rows. Sector 3 corresponds to the less chlorophyllian zones. It is the only sector with drip irrigation, which from February to March 2001 is low (23 mm). The more efficient is plant water regulation, the lower are chlorophyllian responses in all other plots. In diagonal former river channels, the very chlorophyllian class named "chlorophyllian biomass+++" is of limited extent. Grass-covered zones in July (in the "Soil image") correspond to chlorophyllian biomass in the "Vine image". Grass-covered zones where grass developed with delay in the “Soil image” (interpreted as less fertile soils) correspond to “low chlorophyllian biomass” classes in the “Vine image”.

Sector 4: this sector is characterized by vinestocks aged 14-15 years and 3 333 to 4 000 plants/ha, 62.5 mm irrigated from February to March 2001. Row orientation is variable. Variations in the vine chlorophyllian response are due to soil, rather then row orientation. A diagonal mark is interpreted as an old pathway, corresponding to very chlorophyllian class named "chlorophyllian biomass+++".

Sector 5: this sector corresponds to the grass-covered sector localized North-East. It is characterized by 3 333 plants/ha, vinestocks aged 12-13 years and East-West oriented rows. Furrow irrigation is the highest of the Property, reaching 112.5 mm from February to March 2001. Diachrony reveals that the spatial organization in both images is very heterogeneous, as well as the soil-vine response, even though dark soils correspond to marked channels leading to vine chlorophyllian classes. Most other organizations do not coincide at both dates, which may be caused by distinct soil management practices (tillage or no tillage).

Modelled terroir units

The 6 nuclei defined correspond to the classes obtained from processing the "Vine image". They only contain pixels belonging to a given selected class. These pure nuclei are ranked by increasing order, from more to less chlorophyllian biomass, and named as follows: "UT1" for the “chlorophyllian biomass+++” class; "UT2" for the "chlorophyllian biomass++” class; "UT3" for the " chlorophyllian biomass+” class; "UT4" for the "chlorophyllian biomass-" class; "UT5" for the "chlorophyllian biomass--" class and lastly, "UT6" corresponds to the “chlorophyllian biomass---” class. The OASIS classifier was applied with a ‘3 × 3 pixels’ moving window: such window size is likely to give rather compact classes, all together with keeping the classes information (Fig. 3), whereas ‘5 × 5’ window size is too large and leads to degrade such information. The image of distances indicates that most of the studied area is rather well classified, with even some sectors well classified.

2. Discussion

The studied area shows a vine response consistant with soil, owing notably to the presence of former river channels and irrigation modes. The diagonal linear patterns of these channels were not visible in 15-m resolution Aster images of both January 2001 and October 2000 (Parra et al., 2002). The chlorophyllian biomass levels identified are roughly consistant with vine vigour notes in the field by the vine-growers in 2001 (Parra Emilfork, 2004), though such comparison is not easy: in particular, vigour notes are given with horizontal viewing whereas satellite imaging is pseudo-vertical; vigour notes are subjective, with a samping number much lower than the number of pixels. Validation of modelled units by physico-chemical data of harvest was not satisfactory as it has to be improved through a densified sampling scheme.

The OASIS classifier enabled to simplify the results obtained from classifying the "Vine image". However, applying a ‘3 × 3 pixels’ moving window means that spatial resolution decreases from a 4-m pixel to a 12-m pixel. Such a result could have also stemmed from a median filter: in that, it would be of greater interest defining non-pure nuclei which really correspond to patterns of vegetation classes, and for which the resolution degradation is likely to keep the information specific to the very high resolution. The diachronic approach could be improved by comparing images of equal resolutions and of the same vine cycle.

Conclusions

Very high resolution Spot and Ikonos multispectral images enable to map both soil and vine chlorophyllian biomass spatial variability, which leads to propose a demarcation of the Property into modelled terroir units. The detailed level given by very high resolution is higher than that of the plots boundaries. As such demarcation intersects plots, it questions the spatial management according to plots, as it is practiced presently and requires a more densified viticultural sampling scheme for validation.

Literature cited

Carbonneau, A., 2002. Climat et sol : critères d’évaluations et effets sur le comportement de la vigne. In : V. Sotés (Ed.). Proc. 3° Simp. Int. « Zonificación vitivinícola », May 2000, Tenerife (Spain). CD-Rom.

Carsoulle J., 1997. Enherbement permanent du vignoble. Influence sur la production viticole. Le Progrès Agricole et Viticole, 114 (4), 87-92.

Deloire A., Carbonneau, A., Wang, Z., & Ojeda, H., 2004. Vine and Water, a short review. J. Int. Sci. Vigne Vin,, 38, 1, 1-13.

Deloire A., Lopez, F., & Carbonneau, 2002. Réponses de la vigne et terroirs. Eléments pour une méthode d’étude. *Le Progrès Agricole et Viticole*, 4, 78 – 86.

Dolédec, A.F., 1995. Recherche des composantes principales des terroirs viticoles afin d'élaborer un outil d'aide à la gestion au moyen d'observatoires et de traitements statistiques de données spatialisées. Application au vignoble champenois. PhD Thesis, Institut National Agronomique Paris-Grignon, 16, rue Claude Bernard, 75005 Paris, France.

Dolédec, A. F. , Panigaï, L., Descotes, A., Moncomble, D., Cluzeau, D., Pérès, G., & Chaussod, R., 2003. Enherbement permanent et préservation des terroirs en Champagne. Le Progrès Agricole et Viticole, Montpellier France, 120 (7), 151-154.

Dry, P., 2000. Canopy management for fruitfulness. Australian Journal of Grape and Wine Research Australia, 6 (2), 109-115.

Escadafal R. 1989. Caractérisation de la surface des sols arides par observation de terrain et par télédétection. Ph-D thesis, Université Paris-VI, 1989 ; 317 p.

Girard, M.C., & Girard, C.M., 2003. Processing of remote sensing data. Balkema publishers, Rotterdam.

Hall A., Lamb, D.W., Holzapfel, B., & Louis, J., 2002. Optical remote sensing applications in viticulture : a review. Australian Journal of Grape and Wine research, 8, 36-47.

Johnson, L.F., Lobitz, B. , Armstrong, R., Baldy, R., Weber, E. , DeBenedictis, J., & Bosch, D., 1996. Airborne imaging aids vineyard canopy evaluation. California Agriculture, 50/4, 14-18.

Johnson, L.F., 2003. Temporal stability of an NDVI-LAI relationship in a Napa Valley vineyard. Australian Journal of Grape and Wine Research, 9, 96-101.

Johnson, L., Bosch, D., Williams, D., & Lobitz, B., 2001. Remote sensing of vineyard management zones: implications for wine quality. Applied Engineering in Agriculture, 17, 557-560.

Johnson, L.F., Roczen, D.E., Youkhana, S.K., Nemani, R.R., & Bosch, D.F., 2003. Mapping vineyard leaf area with multispectral satellite imagery. Computers and Electronics in Agriculture, 38, 33-44.

Johnson, L., & Pierce L., 2004. Indirect measurement of leaf area index in California North Coast vineyards. HortScience, 39, 236-238.

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 à climat semi-continental (Alsace). PhD Thesis, Dijon University, Dijon, France.

Morlat, R., Robichet, J., Sigogne, M., Remoué, M., Venin, G., Léon, H., & Asselin, C., 1984. Influence de la densité de plantation et du mode d'entretien du sol sur l'alimentation minérale de la vigne. Connaissance Vigne Vin, 18, 83-94.

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 la Moyenne Vallée de la Loire. PhD Thesis, University of Bordeaux II, Bordeaux, France.

Parra, P., Vaudour, E., Girard, M.C., & Holzapfel, E., 2002. Spatial characterization of land use in the viticultural Maipo Valley (Chile), using Aster image processing. In: Institut Rhodanien (ed.). Proc. 4° Int. Conference « Zonage Viti-vinicole», 17-20 June 2002, Avignon (France). 10 p.

Parra Emilfork, P., 2004. Apport de la télédétection à la délimitation des terroirs en zones viticoles. Etude du Domaine de Tocornal dans la Haute Vallée du Maipo au Chili. PhD Thesis, Institut National Agronomique Paris-Grignon, 16, rue Claude Bernard, 75005 Paris, France.

Riou, C., 1997. Influence agro-viticole de l'effet terroir par l'enherbement des sols. Le Progrès Agricole et Viticole, 114 (10), 232-237.

Sandham, L.A., & Zietsman, H.L., 1997. Surface temperature from space : a case study in the South Western Cape of South Africa. South African Journal of Enology and Viticulture, 18, 2, 25-30.

Santibáñez, F., Morales, L., De la Fuente, J., Cellier, P., & Huete, A., 1997. Topoclimatic modeling for minimum temperature prediction at a regional scale in the Central Valley of Chile. Agronomie, 17, 307-314.

Seguin G., 1970. Les sols de vignobles du Haut-Médoc. Influence sur l'alimentation en eau de la vigne et sur la maturation du raisin. PhD Thesis, University of Bordeaux II, Bordeaux, France.

Tisseyre B., Ardoin, N., & Clipet, C., 1999. Mesure des paramètres de rendement et de qualité en viticulture de précision. In : Stafford, J.V. (Ed.). Proceedings of the Second European Conference on Precision Agriculture, Odense, Denmark. Sheffield Academic Press, Sheffield, UK. pp 319-330.

Van Leeuwen, C., 1991. Le vignoble de Saint-Emilion, répartition des sols et fonctionnement hydrique, incidences sur le comportement de la vigne et la maturation du raisin. PhD Thesis, University of Bordeaux II, Bordeaux, France.

Vaudour, E., 2003. Les terroirs viticoles. Définitions, caractérisation et protection. Dunod, Paris.

Vaudour, E., 2001. Les terroirs viticoles. Analyse spatiale et relation avec la qualité du raisin. Application au vignoble AOC des Côtes-du-Rhône méridionales. PhD Thesis, Institut National Agronomique Paris-Grignon, 16, rue Claude Bernard, 75005 Paris, France.

Wassenaar, T., Baret, F., Robbez-Masson, J.M., Andrieux, P., 2001. Sunlit soil surface extraction from remotely sensed imagery of perennial, discontinuous crop areas; the case of Mediterranean vineyards. Agronomie, 21, 235-245.

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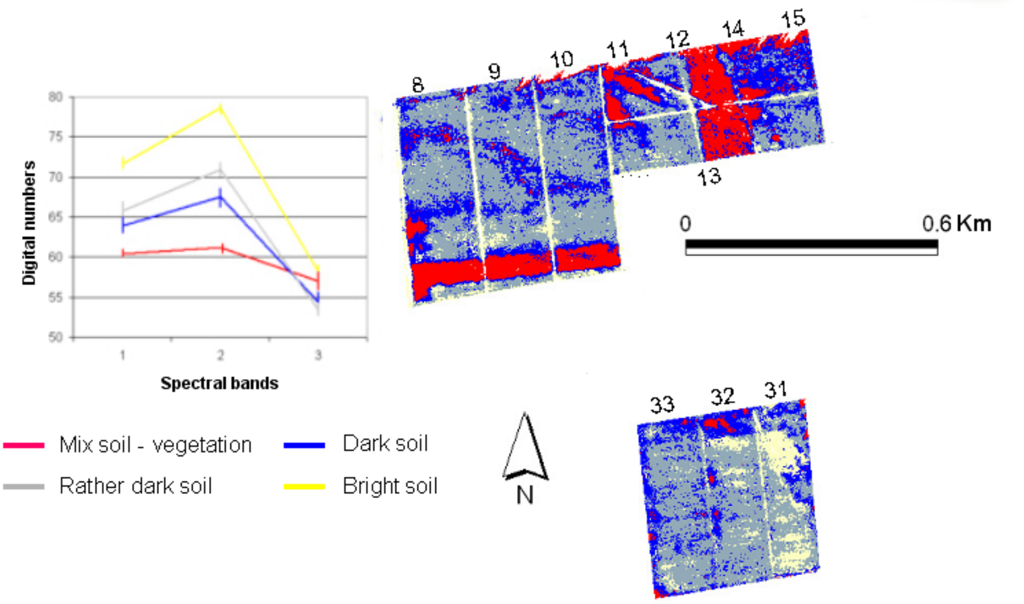

Fig. 1. Digital characteristics and spatial distribution of the 4 classes obtained from classifying the bare surfaces of the «Soil image» (17 July 2002, no grass-cover)

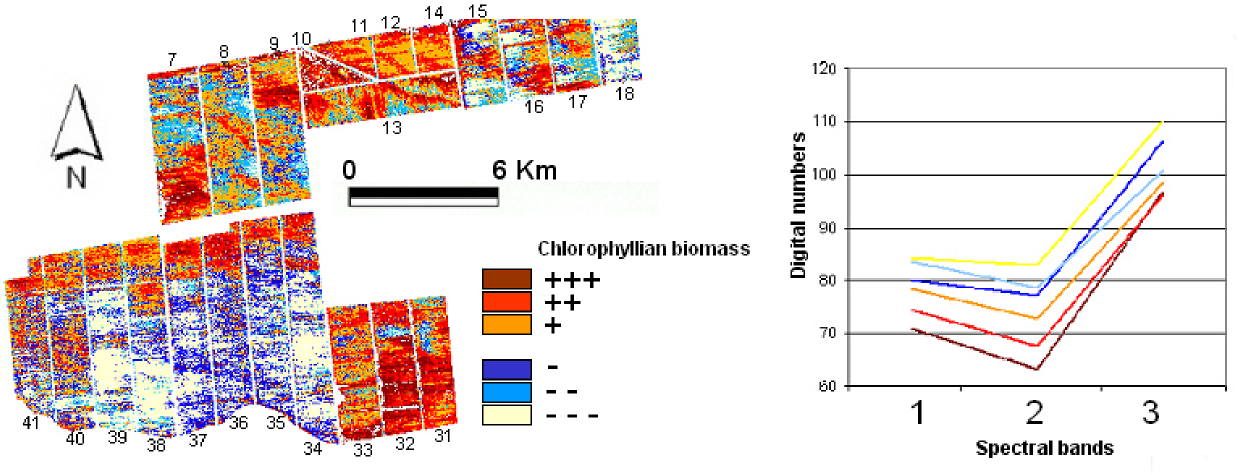

Fig. 2. Digital characteristics and spatial distribution of the 6 classes obtained from classifying the «Vine image» (17 March 2001)

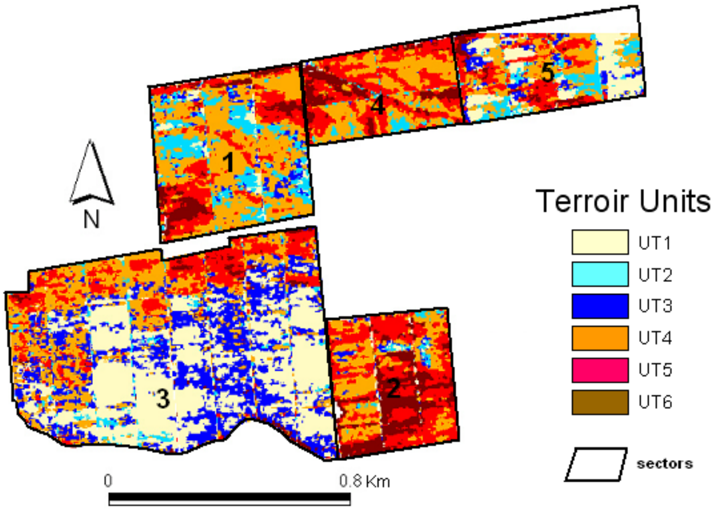

Fig. 3. Modelled terroir units resulting from structural analysis of the classified “Vine image”