CLASSIFYING VINEYARDS FROM SATELLITE IMAGES : A CASE STUDY ON BURGUNDY'S CÔTE D'OR

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Abstract

Aim : To use Remote Sensing imagery and techniques to differentiate categories of Burgundian vineyards.

Methods and results : A sample of 201 vine plots or "climats" from the Côte d'Or region in Burgundy was selected, consisting of three vineyard categories (28 Grand Cru, 74 Premier Cru, and 99 Communale) and two grape varieties (Pinot noir and Chardonnay). A mask formed by the polygons of these vine plots was made and projected on four satellite images acquired by the ASTER sensor, covering the Côte d'Or region in years 2002, 2003 (winter image), 2004 and 2006. Mean reflectances were extracted from pixels within each polygon for each of the nine spectral bands (visible and infrared) covered by ASTER. The database had a total of 797 reflectance spectra assembled over the four images. Statistical discriminant analysis of percentage classification accuracy was made separately for Côte de Nuits and Côte de Beaune, and for each year. Results showed that for individual years and Côtes, classification accuracy for vineyard category was as high as 73.7 % (Beaune 2002) and as low as 66.7 % (Beaune 2003). There were no significant differences in accuracy between spring, summer and winter images. Classification accuracy for grape variety in Côte de Beaune over the four study years was between 73.5 % for Pinot noir climats in 2004 and 91.9 % for Chardonnay climats in 2006, including the winter image. Concerning the vegetation index NDVI, there were no significant differences between vineyard categories.

Conclusions : Satellite data is shown to be functional to reveal vineyard quality. Spectral differences between categories of Burgundian vineyards are at least partially due to terroir characteristics, which are transmitted to vine and vine canopy.

Significance and impact of the study : This work indicates that Remote Sensing techniques can be used as an auxiliary tool for the monitoring of vineyard quality in established viticultural regions and for the study of quality potential in new regions.

Key words : Burgundian climats, Remote Sensing, vineyards spectra, leaf reflectance, satellite images

Résumé

Objectif : Différencier les catégories de parcelles du vignoble bourguignon par l'utilisation d'images satellites.

Méthodes et résultats : Un échantillon de 201 parcelles ou "climats" de la Côte d'Or en Bourgogne a été sélectionné, formé par trois catégories de vignobles (28 Grand Cru, 74 Premier Cru et 99 Communale) et deux cépages (Pinot noir et Chardonnay). Un masque composé par les polygones de ces parcelles a été construit et ensuite projeté sur quatre images satellites de la région, collectées par le senseur ASTER en 2002, 2003 (en hiver), 2004 et 2006. Les réflectances moyennes pour les pixels à l'intérieur de chaque polygone ont été calculées pour chaque année et pour chacune des neuf bandes spectrales (visible et infrarouge). La base de données est formée par 797 spectres de réflectance. Des analyses discriminantes du pourcentage d'exactitude du classement ont été faites séparément pour Côte de Nuits et Côte de Beaune et pour chaque année. Les résultats montrent que la classification au niveau des catégories de vignoble a été précise entre 66,7 % (Beaune 2003) et 73,7 % (Beaune 2002). Aucune différence significative dans la précision n'a été trouvée entre les saisons de l'année des images (printemps, été et hiver). Pour la séparation des cépages sur la Côte de Beaune, la précision de l'analyse discriminante a été entre 73,5 % pour les parcelles de Pinot noir en 2004 et 91,9 % pour les parcelles de Chardonnay en 2006, comprise l'image d'hiver. Pour l'indice de végétation NDVI, aucunes différences significatives entre les catégories n'ont été trouvées.

Conclusion : L'analyse spectrale des données satellitaires peut donner une indication de la qualité d'un vignoble bourguignon. Les différences spectrales entre les catégories de vignobles sont dues au moins en partie aux propriétés du terroir transmises à la vigne.

Signification et impact de l'étude : Ce travail montre que la télédétection peut être un outil supplémentaire pour l'observation de régions viticoles établies, et aussi pour l'étude de la qualité potentielle attendue dans de nouvelles régions.

Mots clés : climat bourguignon, télédétection, spectre des vignobles, réflectance des feuilles, images satellites

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INTRODUCTION

The observation of Earth from remote platforms like airplanes or satellites has proved to be a powerful resource for land studies, with applications to geology, agriculture, environmental sciences, urban and marine monitoring, and many other fields. Presently, most of these Remote Sensing investigations are performed using digital images collected from satellites, which provide low-cost data, with the advantage of being re-acquired at new over-flights. The typical Remote Sensing process involves cameras and sensors aboard the satellite, which collect sunlight reflected from the Earth's surface; during reflection by types or classes of surface cover, like soil or vegetation, the solar spectrum undergoes modifications. The resulting reflectance spectra carry characteristic features of the classes present in the imaged surface and identification of these classes is possible. For example, reflectance spectra from plants are characterized by low reflectance in visible light, with a peak at 550 nm due to chlorophyll, which is the reason for the green color of vegetation; at near-infrared (NIR) wavelengths there is an abrupt transition towards stronger reflectances (the Red Edge); and at longer wavelengths (the Short-Wave Infrared, SWIR) reflectance falls, carrying the typical features of absorption by water at 1,400 and 1,900 nm. The spectral signatures of minerals or water are quite different, and this allows the identification of classes of soil and land cover in Remote Sensing images which have the adequate spectral sensitivity; for comprehensive reviews on the applications of Remote Sensing imagery to land monitoring, see Jensen (2007) or Campbell and Wynne (2011).

This work deals with reflectance spectra of vineyards as a particular class of vegetation. Applications of Remote Sensing techniques to vineyard studies are still in their infancy. Up until now, the majority of studies have focused on precision viticulture management in private properties of limited surface and, for this reason, are based on airborne sensors, either multispectral or hyperspectral (Bramley and Proffitt, 1999; Zarco-Tejada *et al.*, 2005). Remote Sensing imagery from satellites covers much larger areas and is suitable for regional surveys and monitoring. This field of research is new and much groundbreaking work has to be done. In this aspect, we reported in a series of papers studies performed over several viticultural areas in Europe and South America (Da Silva and Ducati, 2009; Blauth and Ducati, 2010; Ducati *et al.*, 2014). It was demonstrated that Remote Sensing data and techniques allows not only the separation of vineyards from other vegetation, but also, to a certain degree, the identification of grape varieties (Cemin and Ducati, 2011). These possibilities were already perceived from laboratory measurements (Lacar *et al.*, 2001), but now it becomes clear that satellite images have their own potential in viticultural studies. After using satellite images to study vineyards in France (Bordeaux, Champagne, Loire), Chile and Brazil, we now focus our studies on Burgundy´s Côte d'Or. This choice is justified by three basic factors:

a) The hierarchical division of the Burgundian vineyard is historical and emblematical, having been the object of countless studies, but up to the present day few papers, if any, have used observations from space;

b) The typical size of vine parcels in Burgundy is of the order of few hectares, being adequately resolved by multispectral images like those from ASTER sensor;

c) The Côte d'Or region is generally oriented facing east (Pitiot and Servant 2010; Atkinson 2011), and so most vineyards receive the morning sunlight in fairly equal inclinations of solar rays. This fact is relevant since the ASTER imager gets data in the morning (around 10h30 AM). The illumination of parcels, which in general are on gentle slopes, tends to be homogeneous; this perception was gained during several field trips to the region in the last years by the first author.

In Burgundy, the hierarchy of Grand Cru, Premier Cru and more generic appellations (Côtes, Villages, Communales, etc.) seems to be linked to soil characteristics, which are at the very root of the terroir concept (Van Leeuwen and Seguin, 2006). From a principal component analysis, Wittendal (2004) gave weight to a widespread perception, indicating that most Grand Cru soils have a particular structure that is significantly different from the soils of other categories. Therefore, the objective of this investigation was to verify if these quality categories, which are transmitted from soil to wine, are also transmitted from soil to vine leaves and if they can be detected in the spectral information contained in the images. This is because the observation parameter in digital images, the reflectance, originates mainly from vine leaves reflecting sunlight, if we are using non-winter data. At the high plant density used in Burgundy (up to 10,000 vines/hectare), the soil is almost entirely covered by the plant canopy; besides, at the moment of image acquisition (10h30 AM),

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there is an important projection of shadow between vine rows and little sunlight is reflected from the shadowed soil. This point will be analysed in greater detail in the Discussion section, but for now, it can be stated, for practical purposes, that the reflected light in images acquired during the vegetative cycle comes essentially from vine leaves.

MATERIALS AND METHODS

1. Image acquisition

Images from the ASTER sensor, which is aboard the Terra satellite, were acquired through the NASA website reverb.echo.nasa.gov/reverb, in the context of a research project submitted by the authors and approved by NASA. Extensive information on the ASTER sensor can be found in Abrams *et al.* (2002). The spatial resolution, or pixel size of the images, is 15 meters at the first three spectral bands in the visible and near-infrared (VNIR) subsystem, and 30 meters at the six bands in the SWIR subsystem. These combined features allow deeper analysis of reflectance compared with those of other orbital sensors like Landsat, CBERS or ALOS. Image dates were September 19, 2002 ; June 9, 2004 ; and September 6, 2006, corresponding to late spring or late summer in the Northern hemisphere. To look for pure soil effects, we also analysed a winter image (February 15, 2003), where no grape leaves were covering the soil and hiding it from satellite view. The usual treatments were applied : atmospheric correction (Berk *et al.*, 2006) and compensation for the crosstalk effect (Iwasaki and Tonooka 2005). An additional treatment was made concerning pixel size ; to run the atmospheric correction algorithm it is necessary that all nine bands be at the same spatial resolution (either 15 meters or 30 meters). When studying vine parcels of a few hectares, the spatial resolution has to be as high as possible, and to take full advantage of the three higher resolution (15 meters) bands, we resampled the six 30-meter bands to match the 15-meter pixels, a procedure already used and discussed elsewhere (Mather, 1999 ; Altaweel, 2005).

2. Vineyard selection

The Côte d'Or region has about 1,200 vine parcels which are climats or lieu-dits. This is a large number, and to study them all would be a major constraint to a project whose prime objective is to test the spectral recognition of vineyard categories. Thus, we looked for a sample which would be representative of the three categories (Grand Cru, Premier Cru and Communales), having as selection criteria parcels with adequate areas (not too small, i.e., with more than 40 pixels of 225 m^2 each), with adequate geometry (the more square, the better), and evenly distributed over the Côte d'Or region. The maps of Côte de Nuits and Côte de Beaune by Pitiot and Poupon (2009) were used for the selection of vine parcels. The final sample was formed by 201 plots : 28 Grand Cru (10 in Beaune, 18 in Nuits), 74 Premier Cru (51 in Beaune, 23 in Nuits), and 99 Communales (53 in Beaune, 46 in Nuits), this last category corresponding to vineyards which are lieu-dits and which are neither Grand Cru nor Premier Cru. The complete list of these vineyards is given in Appendix A.

A mask containing the polygons of these vineyards was generated based on the maps of the region, which were georeferenced in the same frame of reference as the satellite images. This mask was then superposed on the ASTER images, on which the selected parcels could be identified. For each climat or lieu-dit, the mean reflectance of all pixels inside a polygon was calculated for each one of the nine spectral bands. Great care was taken in doing the mask to ensure that each polygon was entirely inside the climat, avoiding contamination from other spectral classes, like roads, buildings or other vegetation classes. The selected polygons had from 40 to 140 pixels, corresponding to areas within climats from 0.9 to about 3 hectares, since a pixel has 15 m x 15 m or 225 m^2.

The final sample had 797 reflectance spectra of 201 climats of the three vineyard categories. The sample was divided in eight files, one file for each year (2002, 2003, 2004, and 2006) and for each Côte. The exact number of each category in each year/image varied slightly because variations in image quality sometimes made it impossible to accurately visualize certain climats. The sample also contained information on grape variety. In Côte de Nuits, only 2 out of the 87 selected parcels were Chardonnay, expressing the massive dominance of Pinot noir in the northern part of Côte d'Or. On the other hand, in Côte de Beaune many parcels of the Communale category and some of Premier Cru were planted with both grape varieties. In the eight files forming the database, each line contained the climat number and name, the category code, the grape variety, and all nine mean reflectance values. Figure 1 shows how some climats appear in the satellite image.

3. Statistical analysis

A statistical discriminant analysis with respect to vineyard category was performed using the nine

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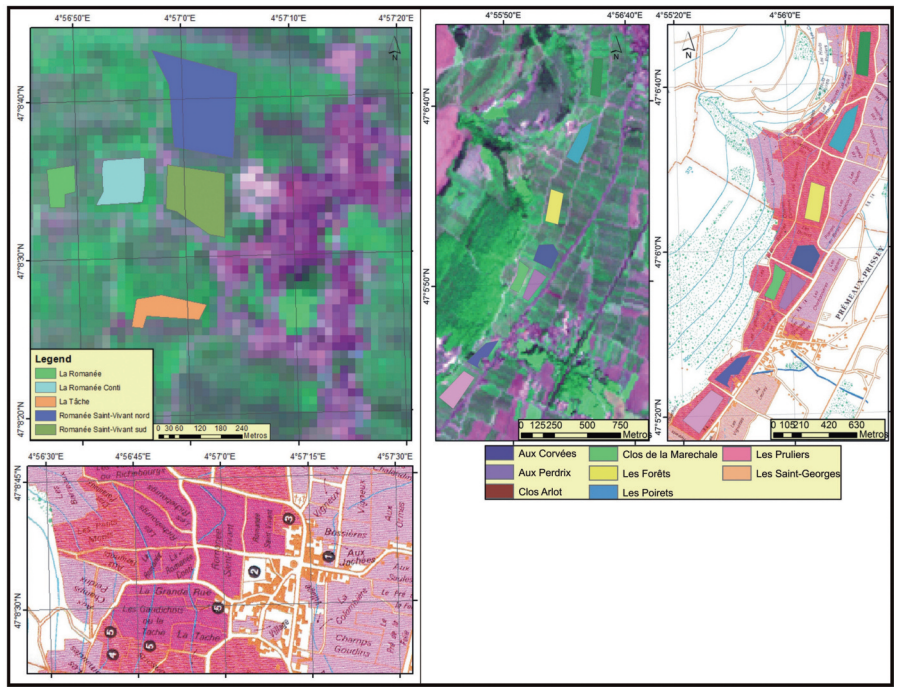


Figure 1. Examples of polygons superposed on an ASTER satellite image and the corresponding maps. Some selected climats in two areas of Côte de Nuits are shown.

spectral bands of reflectance spectra for each year and each Côte, since a preliminary analysis using the whole sample revealed that seasonal and spatial differences increased noise level.

An additional analysis using one-way ANOVA with Tukey post-hoc multiple comparisons test was made, looking for which spectral band could be more relevant to separate one vineyard category from the others.

Another discriminant analysis was performed with respect to grape variety for the Côte de Beaune files. Since each image was studied separately, we included the winter data in the analysis, although in winter there are no vine leaves to reflect sunlight. We also performed two separate analyses for grape varieties. The first one was with Pinot noir (49 parcels) and Chardonnay (37 parcels); all 28 mixed parcels were excluded from this analysis. The second analysis considered all the three grape groups: Pinot noir, Chardonnay and Pinot/Chardonnay. Preliminary tests showed that the discriminant analysis performed better for the pure groups. This was expected because in parcels with spectral mixture at pixel level, the exact variety proportions are unknown. Therefore, we restricted the analysis to the mono-varietal vineyards.

An additional analysis was performed concerning a vegetation index, in this case the Normalized Difference Vegetation Index (NDVI), defined as (Tucker, 1979):

$$NDVI = (R_{IR} - R_{VIS})/(R_{IR} + R_{VIS}) \qquad (1)$$

where R_{IR} is the reflectance at the near infrared, which in ASTER subsystems is band 3 (0.760–0.860 µm), and R_{VIS} is the reflectance at red (0.630–0.690 µm), which is band 2. NDVI values were calculated for all 797 spectra and an ANOVA analysis was made comparing the mean values of NDVI with respect to vineyard category.

RESULTS

With respect to vineyard category, the application of discriminant analysis to Côte de Beaune (Table 1) and Côte de Nuits (Table 2) showed that for individual years and Côtes, classification accuracy was as high as 73.7 % (Beaune 2002) and as low as 66.7 % (Beaune 2003).

Results from the ANOVA test which investigated the more relevant spectral bands for vineyard category discrimination were as follows: Grand Cru climats with Pinot noir grapes had higher mean values of reflectance in bands B2, B4, B5, B6, B7 and B8; that is, in these six bands, Grand Cru plots were different from both Premier Cru and Communale plots. Numbers are less clear for Chardonnay Grand Crus. No systematic differences were observed, and in

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Table 1. Discriminant analysis (vineyard category) for Côte de Beaune

Year		Category	Predicted Group Membership			Total
			Communale	Grand Cru	Premier Cru	
2002 Original	Count	Communale	37	3	13	53
		Grand Cru	2	8	0	10
		Premier Cru	9	3	39	51
	%	Communale	69.8	5.7	24.5	100
		Grand Cru	20	80	0	100
		Premier Cru	17.6	5.9	76.5	100
2003 Original	Count	Communale	41	2	10	53
		Grand Cru	1	7	2	10
		Premier Cru	12	11	28	51
	%	Communale	77.4	3.8	18.9	100
		Grand Cru	10	70	20	100
		Premier Cru	23.5	21.6	54.9	100
2004 Original	Count	Communale	37	4	10	51
		Grand Cru	0	10	0	10
		Premier Cru	13	5	32	50
	%	Communale	72.5	7.8	19.6	100
		Grand Cru	0	100	0	100
		Premier Cru	26	10	64	100
2006 Original	Count	Communale	37	3	11	51
		Grand Cru	0	8	2	10
		Premier Cru	11	6	34	51
	%	Communale	72.5	5.9	21.6	100
		Grand Cru	0	80	20	100
		Premier Cru	21.6	11.8	66.7	100

Percentage of original grouped cases correctly classified: 2002, 73.7 %; 2003, 66.7 %; 2004, 71.2 %; 2006, 70.5 %.

some bands, Communale was separated from Grand Cru and Premier Cru and in others, Grand Cru was separated, with higher or lower values, from the other classes. It seems that for Chardonnay, the Grand Cru category is separated in a more complex way.

Grape variety results for Côte de Beaune, over the four years, are presented in Table 3. Accuracy was as low as 73.5 % for Pinot noir parcels (2004) and as high as 91.9 % for Chardonnay parcels (2006). It is worth of note that the separation of Pinot noir from Chardonnay vine plots was fairly well done even using 2003 winter data (79.6 % for Pinot noir and 89.2 % for Chardonnay), performing better than June 2004 data and with an accuracy similar to late summer data for 2002 and 2006.

Results for NDVI are shown in Table 4. Not surprisingly, NDVI values for all vineyard categories were smaller for the 2003 winter image (mean values around 0.25), being typical of classes like soil, which is exposed at this season. The index increased as the vegetative cycle progressed and was 0.46 for the June 2004 image in the two regions. The NDVI index was higher for both late summer images (Sept. 2002 and 2006), with mean values between 0.62 and 0.64. However, there were no significant variations of NDVI comparing vineyard category.

DISCUSSION

1. Factors building up reflectance

An initial point to be discussed is if reflectance data from a vineyard, acquired by a satellite, contains information only from vine leaves or if this information is contaminated by other radiant sources, like soil, roads, or buildings. As for pixels located outside the vine parcels, we have already made it clear that great care was taken to precisely extract data well inside the selected parcels. The question is if within-vineyard features like soil, terrain slope, and row orientation play relevant roles in reflectance responses. In a previous paper we studied these influences in a different region, the Loire Valley (Ducati *et al.*, 2014). We will now present a short summary of that lengthy study. We argued that the soil contribution to reflectance is strongly dependent

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Table 2. Discriminant analysis (vineyard category) for Côte de Nuits

Year			Category	Predicted Group Membership			Total
				Communale	Grand Cru	Premier Cru	
2002	Original	Count	Communale	36	3	6	45
			Grand Cru	3	12	3	18
			Premier Cru	3	8	11	22
		%	Communale	80.0	6.7	13.3	100
			Grand Cru	16.7	66.7	16.7	100
			Premier Cru	13.6	36.4	50	100
2003	Original	Count	Communale	33	6	7	46
			Grand Cru	4	10	4	18
			Premier Cru	2	4	17	23
		%	Communale	71.7	13.0	15.2	100
			Grand Cru	22.2	55.6	22.2	100
			Premier Cru	8.7	17.4	73.9	100
2004	Original	Count	Communale	32	5	9	46
			Grand Cru	2	14	2	18
			Premier Cru	2	6	15	23
		%	Communale	69.6	10.9	19.6	100
			Grand Cru	11.1	77.8	11.1	100
			Premier Cru	8.7	26.1	65.2	100
2006	Original	Count	Communale	34	6	6	46
			Grand Cru	1	14	3	18
			Premier Cru	3	4	16	23
		%	Communale	73.9	13.0	13.0	100
			Grand Cru	5.6	77.8	16.7	100
			Premier Cru	13.0	17.4	69.6	100

Percentage of original grouped cases correctly classified: 2002, 69.4 %; 2003, 69.0 %; 2004, 70.1 %; 2006, 73.6 %.

Table 3. Discriminant analysis (grape variety) for Côte de Beaune

Year		Grape variety	Predicted Group Membership		Total
			Chardonnay	Pinot noir	
2002 Original	Count	Chardonnay	32	5	37
		Pinot noir	5	44	49
	%	Chardonnay	86.5	13.5	100.0
		Pinot noir	10.2	89.8	100.0
2003 Original	Count	Chardonnay	33	4	37
		Pinot noir	10	39	49
	%	Chardonnay	89.2	10.8	100.0
		Pinot noir	20.4	79.6	100.0
2004 Original	Count	Chardonnay	27	9	36
		Pinot noir	13	36	49
	%	Chardonnay	75.0	25.0	100.0
		Pinot noir	26.5	73.5	100.0
2006 Original	Count	Chardonnay	34	3	37
		Pinot noir	6	43	49
	%	Chardonnay	91.9	8.1	100.0
		Pinot noir	12.2	87.8	100.0

Percentage of original grouped cases correctly classified: 2002, 88.4 %; 2003, 83.7 %; 2004, 74.1 %; 2006, 89.5 %.

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on the amount of illuminated soil, which depends on plant density, row orientation, and the hour and epoch of image acquisition. As for plant density, the standard density in Côte d'Or is about 10,000 plants per hectare; such a high density ensures, during the vegetative cycle, a relatively small soil visibility. However, some soil would still be seen from the vantage point of a satellite, and we have to consider its radiance relative to plant leaves, which can be reduced by shadows projected by the vines.

For this geometrical shadow effect, the proportion P of the inter-row surface that is shadowed by a continuous wall of vines is:

$$P = (h/d) * \tan z * |\sin a| \qquad (2)$$

where h is the row height, d is the distance between rows, z is the Sun's zenithal distance or elevation at a given moment, and a is the lateral illumination angle at the same time, that is, a is the angle between the orientation of a given row and the solar azimuth. Here, the angle a modulates the shadow's length because when $a = 0^{o}$, the row is oriented towards the Sun and the inter-row soil is entirely illuminated. In equation (1), the proportion P assumes values between 0 and 1, the value 1 corresponding to the extreme situation where the whole area between vine rows is in total shadow.

Table 4. Vegetation index (NDVI) for Côte de Beaune and Côte de Nuits

Côte	epoch	# vineyards	NDVI min	NDVI max	Mean	Std. Dev.
Beaune	Sept. 2002	Comm. (53)	.53	.70	.64	.040
		Gr. cru (10)	.53	.74	.61	.068
		Pr. cru (51)	.48	.74	.62	.052
		Total (114)	.48	.74	.64	.049
	Feb. 2003	Comm. (53)	.20	.29	.24	.020
		Gr. Cru (10)	.20	.30	.24	.029
		Pr. Cru (51)	.20	.33	.24	.030
		Total (114)	.19	.33	.24	.025
	June 2004	Comm. (51)	.39	.54	.48	.033
		Gr. Cru (10)	.38	.48	.44	.033
		Pr. Cru (51)	.33	.57	.45	.048
		Total (111)	.33	.57	.46	.043
	Sept. 2006	Comm. (51)	.57	.69	.64	.031
		Gr. Cru(10)	.55	.66	.61	.034
		Pr. Cru (51)	.53	.68	.63	.040
		Total (112)	.53	.69	.63	.037
Nuits	Sept. 2002	Comm. (45)	.51	.72	.63	.043
		Gr. Cru (18)	.50	.78	.65	.071
		Pr. Cru (22)	.50	.70	.63	.058
		Total (85)	.50	.78	.63	.054
	Feb. 2003	Comm (46)	.22	.32	.27	.022
		Gr. Cru (18)	.22	.32	.26	.026
		Pr. Cru (23)	.21	.34	.26	.030
		Total (87)	.21	.34	.26	.025
	June 2004	Comm. (46)	.41	.51	.47	.023
		Gr. Cru (18)	.40	.49	.45	.023
		Pr. Cru (23)	.40	.51	.45	.033
		Total (87)	.40	.51	.46	.026
	Sept. 2006	Comm. (46)	.47	.69	.61	.050
		Gr. Cru (18)	.55	.74	.66	.055
		Pr. Cru(23)	.48	.70	.62	.053
		Total (87)	.47	.74	.62	.054

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In Ducati *et al.* (2014) we showed that a shadowed soil has little reflectance compared to fully-illuminated leaves. But it is seen that the amount of illuminated soil is critically dependent on row orientation; if in Loire we perceived that row orientations in vineyards are almost random, in Côte d'Or we saw during our field trips, further supported by visual inspection of high-resolution satellite images available via Internet services, that there is a certain dominance of down-hill rows. The exact geographical direction of these down-hill rows, however, varies depending on the local slope, which can favor an east exposure as well as north-east, south-east and other more extreme exposure. The Sun's position at the moment of image acquisition (10 h 30 AM) was east, and the Sun's zenithal distance in our images never exceeded 65°. Therefore, for the vineyards with down-hill rows, there is a certain amount of sunlight illuminating the soil between rows and its contribution may be considered.

However, for practical purposes, we will not discuss this issue further. This is due to the fact that during our field trips we did not detect any correlation between row orientation and vineyard category. In fact, we even observed that in those Grand Cru vineyards that are not "monopoles" the orientations of vine rows vary considering the plots inside the appellation; this is observed, for example, in the Clos-Vougeot and Échezeaux terrains and, of course, in the two other categories of this study, Premier Cru and Communale. Therefore, even if a contribution to pixel reflectance from the soil exists, this contribution is prone to be common to all three studied categories and would not be a differentiation factor in our study. This conclusion is not surprising, since if row orientation had been relevant to quality discrimination in Burgundy, the categories would have been separated by their respective row orientations a long time ago, which is not the case.

Another consideration, as stated at the beginning of this section, is terrain slope. The less prestigious vineyards in Burgundy are located over the plains on the east side of RN74, but in our study we have selected only a few plots in that zone. By far, the larger part of our sample was composed of vine plots on the hilly part. Here two points must be considered. The first one is that there is no clear slope-based criterion to separate the three categories in our sample; this is simply not observed. The second point is that the reflectance has its origin in vine leaves, and the amount of reflectance depends on the relative orientation of the plant leaf surface with respect to sunlight. However, plant leaves orient themselves to maximize sunlight absorption and do not follow terrain slope; therefore, leaf orientation, and so the part of pixel reflectance that is due to vegetation, tends to be independent of slope.

As a final remark on the possible relevance of slope and solar orientation to vineyard quality in Côte d'Or, we note that these variables were already included in the study by Wittendal (2004), with no positive results.

2. Our results

As presented in the Results section, category discrimination was fairly good over all four images. It could be expected that discrimination accuracy would be poorer for the winter data, since the reflected light comes from the soil, with little contribution from vegetation; however, the difference of winter data with respect to spring or summer data was small. This suggests that spectral differences between categories come primarily from the soil and when the soil is covered by vine leaves these differences persist and even seem to be reinforced by what the soil communicates to plant leaves. Another result that may deserve deeper investigation is the parcels that were placed in a different category in discriminant analysis. Overall, the results indicate that about 30 % of all parcels presented spectral features typical of other categories. For example, some climats, which are formally classified as being generic appellations, carried spectral features derived from soil/leaf reflectance that put them in higher categories; the opposite also happened. For each region we had four images, and so we had four spectra treated separately in discriminant analysis. Uncertainties in reflectance determination could eventually change a spectrum to the point of putting it in another category, but some systematic changes did appear. These cases were as follows: one climat of the Communale class was considered to be Grand Cru in all four images; seven Communale climats were classified as Premier Cru four times; the opposite, Premier Cru classified as Communale, happened four times; and two Premier Cru climats were classified as Grand Cru in all four images. Visual inspection of images did not reveal any irregularities, and thus these cases deserve further and deeper investigation, possibly including more detailed soil information and field inspection.

Between 70 % and 100 % of Grand Cru vineyards were correctly identified in Beaune; these numbers were between 55.6 % and 77.8 % in Nuits. The question is: in our satellite reflectance data, what differentiates the Grand Cru category from the

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others? Results showed that a systematically higher reflectance seems to be real for Pinot noir, and that for Chardonnay the differentiation process seems to be more subtle. It is known that ASTER satellite bands B4 to B8 are sensitive to water, meaning that higher water content in a target will reduce reflectance. Pinot noir Grand Crus had higher reflectance. Whether this means less water in leaves and soil is not totally clear. Atkinson (2011) suggested that Grand Cru soils have a more stable capacity of water storage, due to sub-soil characteristics; peculiarities in top-soil, the one that is observed from space, seem to be less evident. This question can be better understood in future studies, based on more detailed spectral information and a wider database.

Parcels with Chardonnay were well separated from those with Pinot noir. Again, the question is whether this is due to vegetation or soil. We already mentioned that during the vegetative season the soil is well covered by the canopy and also that this soil tends to be in shadow at the moment of image acquisition. This perception leads us to believe that the separation is due to spectral differences between the two varieties, expressed by leaf reflectance. In another investigation (Da Silva and Ducati, 2009) we demonstrated that red and white grapes could be spectrally separated, the cause being the anthocyanin pigment which is present in leaf cells of red grapes. However, the 2003 winter result provides a deeper insight, since we have only soil reflectance and separation is still well done. This is for Côte de Beaune, where the best terroirs for Chardonnay and Pinot were pinpointed by centuries of study. The extremely variable Burgundian soil was and continues to be determinant for these choices (Fanet, 2008; Pitiot and Servant, 2010), and in a limestone-dominated environment, subtle differences made Chardonnay to be frequently placed where there is a certain dominance of clay with marl-limestone. Other factors can also play a role, like terrain orientation, with often more south and south-west facing parcels for Chardonnay and a tendency for Pinot noir to occupy the higher parts of the hilly landscape. All these factors may induce spectral differences in the infrared. On the one hand, a southern exposure would make the top layers of soil drier, possibly increasing reflectance. But on the other hand, more clayed, marl-limestone terrains retain more water, and it is well known that higher soil humidity reduces the reflectance at infrared (Bowers and Hanks, 1965); moreover, if Chardonnay is more frequently placed at the lower part of hills, again humidity will be higher, and both factors would reduce reflectance. Therefore, as for vineyard category discrimination, terrain and soil-terroir are the ultimate differentiation factors.

CONCLUSION

We have shown that satellite data is functional to reveal vineyard quality. This can be seen as surprising. Spectral differences should come essentially from soil features, which are transmitted to the vine and to vine leaves. In this study, Remote Sensing techniques were valuable in the characterization of terroirs, in this case with respect to vineyard quality. It can be noted that the ultimate factor defining quality is the resulting wine, and wine quality results not only from the soil components of the terroir concept but also from viticultural and winemaking practices. These non-geochemical factors can perhaps explain part of the « wrong » identifications commented in the Discussion, keeping the following comment in mind (Thackrey 2001): « I believe that the quality of French wine is due to a French genius for viticulture and winemaking, (...), not to the subsoil ». The fact that the differences between these climat categories are at least partially due to terroir characteristics suggests that terroir, or more precisely, the soil, influences the vine and vine canopy up to the point that detection of vineyard quality by Remote Sensing becomes possible.

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Appendix A. Climats and lieu-dits included in this study

Climat	Commune	Category	Côte
Sur Le Bois Nord	Cheilly-lès-Maranges	Communale	Beaune
Sur Le Bois Sud	Cheilly-lès-Maranges	Communale	Beaune
Les Charmes Dessus	Santenay	Communale	Beaune
Les Cornières	Santenay	Communale	Beaune
Les Hâtes	Santenay	Communale	Beaune
Les Prarons Dessus	Santenay	Communale	Beaune
Les Champs Claudes	Santenay	Communale	Beaune
Les Benoites	Chassagne-Montrachet	Communale	Beaune
Champs de Morjot	Chassagne-Montrachet	Communale	Beaune
Les Lombardes	Chassagne-Montrachet	Communale	Beaune
Clos Bernot	Chassagne-Montrachet	Communale	Beaune
La Caniere	Chassagne-Montrachet	Communale	Beaune
Les Masures	Chassagne-Montrachet	Communale	Beaune
Le Concis du Champs	Chassagne-Montrachet	Communale	Beaune
Les Chambres	Chassagne-Montrachet	Communale	Beaune
Les Hautés	Auxey-Duresses	Communale	Beaune
La Macabrée	Auxey-Duresses	Communale	Beaune
Les Boutonniers	Auxey-Duresses	Communale	Beaune
Les Famines	Volnay	Communale	Beaune
Les Grands Poisots	Volnay	Communale	Beaune
Les Cras (Pommard)	Pommard	Communale	Beaune
Village	Pommard	Communale	Beaune
Les Prevoles	Beaune	Communale	Beaune
Les Peuillets com.	Savigny-lès-Beaune	Communale	Beaune
Poirier Malchaussé	Chorey-lès-Beaune	Communale	Beaune
Les Pimentiers	Savigny-lès-Beaune	Communale	Beaune
Aux Fourches	Savigny-lès-Beaune	Communale	Beaune
Aux Champs Chardons	Savigny-lès-Beaune	Communale	Beaune
Aux Petits Liards	Savigny-lès-Beaune	Communale	Beaune
Les Beaumonts ouest	Chorey-lès-Beaune	Communale	Beaune
Tue-Boeuf	Chorey-lès-Beaune	Communale	Beaune
Les Bons Ores	Chorey-lès-Beaune	Communale	Beaune
Les Champs Longs	Chorey-lès-Beaune	Communale	Beaune
Les Cras (Aloxe-Corton)	Aloxe-Corton	Communale	Beaune
Les Valoziéres	Aloxe-Corton	Communale	Beaune
Sur Herbeux	Pernand-Vergelesses	Communale	Beaune
La Mort	Ladoix	Communale	Beaune
Les Embazées	Chassagne-Montrachet	Premier Cru	Beaune
Les Grands Clos	Chassagne-Montrachet	Premier Cru	Beaune
La Chapelle	Chassagne-Montrachet	Premier Cru	Beaune
Les Chaumées	Chassagne-Montrachet	Premier Cru	Beaune
Les Fairendes	Chassagne-Montrachet	Premier Cru	Beaune
En Cailleret	Puligny-Montrachet	Premier Cru	Beaune
Les Champs Gain	Puligny-Montrachet	Premier Cru	Beaune
Chassagne	Chassagne-Montrachet	Premier Cru	Beaune
Clos Saint-Jean	Chassagne-Montrachet	Premier Cru	Beaune
Les Chenevottes	Chassagne-Montrachet	Premier Cru	Beaune
Le Montrachet	Chassagne-Montrachet	Grand Cru	Beaune
Bâtard Montrachet S	Puligny-Montrachet	Grand Cru	Beaune
Bâtard Montrachet N	Puligny-Montrachet	Grand Cru	Beaune
Montrachet	Puligny-Montrachet	Grand Cru	Beaune
Chevaller Montrachet	Puligny-Montrachet	Grand Cru	Beaune
Les Tremblots	Puligny-Montrachet	Communale	Beaune
Les Houillères	Puligny-Montrachet	Communale	Beaune
Le Cailleret	Puligny-Montrachet	Premier Cru	Beaune
Les Pucelles	Puligny-Montrachet	Premier Cru	Beaune
Clavaillon	Puligny-Montrachet	Premier Cru	Beaune

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Les Perrieres	Puligny-Montrachet	Premier Cru	Beaune
Les Combettes	Puligny-Montrachet	Premier Cru	Beaune
Les Referts	Puligny-Montrachet	Premier Cru	Beaune
Les Charmes-Dessus	Mersault	Premier Cru	Beaune
Les Levrons	Puligny-Montrachet	Communale	Beaune
Les Reuchaux	Puligny-Montrachet	Communale	Beaune
Corvée des Vignes	Puligny-Montrachet	Communale	Beaune
Le Limozin	Mersault	Communale	Beaune
Les Pelles-Dessous	Mersault	Communale	Beaune
Sous La Velle	Mersault	Communale	Beaune
Les Grands Charrons	Mersault	Communale	Beaune
Les Tillets	Mersault	Communale	Beaune
Les Clous Dessus est	Mersault	Communale	Beaune
Les Clous Dessus ouest	Mersault	Communale	Beaune
Les Vireuils Dessus est	Mersault	Communale	Beaune
Les Vireuils Dessus ouest	Mersault	Communale	Beaune
Le Cromin	Mersault	Communale	Beaune
Les Meix Chavaux	Mersault	Communale	Beaune
Les Clos Roussots est	Maranges	Premier Cru	Beaune
Les Clos Roussots ouest	Maranges	Premier Cru	Beaune
Beauregard	Santenay	Premier Cru	Beaune
La Comme	Santenay	Premier Cru	Beaune
Les Graviéres	Santenay	Premier Cru	Beaune
Les Champs Fulliot	Monthélie	Premier Cru	Beaune
Clos des Chenes	Volnay	Premier Cru	Beaune
En Champans	Volnay	Premier Cru	Beaune
Frémiets	Volnay	Premier Cru	Beaune
Les Bertins	Pommard	Premier Cru	Beaune
Clos de la Commaraine	Pommard	Premier Cru	Beaune
La Refene	Pommard	Premier Cru	Beaune
Clos Blanc	Pommard	Premier Cru	Beaune
Les Grands Epenots	Pommard	Premier Cru	Beaune
Les Petits Epenots 1.SE	Pommard	Premier Cru	Beaune
Les Petits Epenots 2.NW	Pommard	Premier Cru	Beaune
Les Petits Epenots 3.NE	Pommard	Premier Cru	Beaune
Les Epenotes	Beaune	Premier Cru	Beaune
Le Clos des Mouches	Beaune	Premier Cru	Beaune
Les Aigrots	Beaune	Premier Cru	Beaune
Champs Pimont	Beaune	Premier Cru	Beaune
Les Avaux	Beaune	Premier Cru	Beaune
Les Tuvilains	Beaune	Premier Cru	Beaune
Belissand	Beaune	Premier Cru	Beaune
Les Teurons	Beaune	Premier Cru	Beaune
Les Greves	Beaune	Premier Cru	Beaune
Les Cents Vignes	Beaune	Premier Cru	Beaune
Clos du Roi	Beaune	Premier Cru	Beaune
Les Peuillets 1er	Savigny-lès-Beaune	Premier Cru	Beaune
Les Narbantons	Savigny-lès-Beaune	Premier Cru	Beaune
Aux Clous	Savigny-lès-Beaune	Premier Cru	Beaune
Aux Serpentieres	Savigny-lès-Beaune	Premier Cru	Beaune
Aux Vergelesses	Savigny-lès-Beaune	Premier Cru	Beaune
Les Basses Vergelesses	Pernand-Vergelesses	Premier Cru	Beaune
Le Clos du Roi	Aloxe-Corton	Grand Cru	Beaune
Les Bressandes	Aloxe-Corton	Grand Cru	Beaune
Les Renardes	Aloxe-Corton	Grand Cru	Beaune
Les Pougets	Aloxe-Corton	Grand Cru	Beaune
Le Corton	Aloxe-Corton	Grand Cru	Beaune
Le Clos de Magny	Corgoloin	Communale	Nuits
La Montagne	Corgoloin	Communale	Nuits

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Les Chaillots	Corgoloin	Communale	Nuits
Aux Quartiers	Corgoloin	Communale	Nuits
Les Monts de Boncourt	Corgoloin	Communale	Nuits
Aux Fauques	Comblanchien	Communale	Nuits
Belle Vue	Comblanchien	Communale	Nuits
Le Vaucrain	Comblanchien	Communale	Nuits
Les Vignottes	Premeaux	Communale	Nuits
Au Leurey	Premeaux	Communale	Nuits
Preau	Brochon	Communale	Nuits
Vignois	Brochon	Communale	Nuits
Les Vallerots	Nuits-Saint-Georges	Communale	Nuits
Les Longecourts	Nuits-Saint-Georges	Communale	Nuits
Les Chaliots	Nuits-Saint-Georges	Communale	Nuits
Les Charmois	Nuits-Saint-Georges	Communale	Nuits
La Charmotte	Nuits-Saint-Georges	Communale	Nuits
Aux Allots	Nuits-Saint-Georges	Communale	Nuits
Aux Saints Jacques	Nuits-Saint-Georges	Communale	Nuits
Aux Herbues	Nuits-Saint-Georges	Communale	Nuits
Aux Raviolles	Vosne-Romanée	Communale	Nuits
Aux Lavières	Nuits-Saint-Georges	Communale	Nuits
Au Bas de Combe	Nuits-Saint-Georges	Communale	Nuits
Aux Athees	Nuits-Saint-Georges	Communale	Nuits
Les Condemennes	Chambolle-Musigny	Communale	Nuits
Les Babilleres	Chambolle-Musigny	Communale	Nuits
Les Athets	Chambolle-Musigny	Communale	Nuits
Les Herbues	Chambolle-Musigny	Communale	Nuits
Les Porroux	Morey-Saint-Denis	Communale	Nuits
Clos Solon	Morey-Saint-Denis	Communale	Nuits
Les Crais	Morey-Saint-Denis	Communale	Nuits
Les Cognées	Morey-Saint-Denis	Communale	Nuits
Les Crais Gillon	Morey-Saint-Denis	Communale	Nuits
Les Seuvrées	Gevrey-Chambertin	Communale	Nuits
Le Fourneau	Gevrey-Chambertin	Communale	Nuits
Pressonnier	Gevrey-Chambertin	Communale	Nuits
La Burie	Gevrey-Chambertin	Communale	Nuits
Croix des Champs	Gevrey-Chambertin	Communale	Nuits
La Platière	Gevrey-Chambertin	Communale	Nuits
Creux Brouillard	Gevrey-Chambertin	Communale	Nuits
La Justice	Gevrey-Chambertin	Communale	Nuits
Billard	Brochon	Communale	Nuits
Les Jeunes Rois	Brochon	Communale	Nuits
En Auvonne	Couchey	Communale	Nuits
Es Barres	Marsannay-La-Côte	Communale	Nuits
Champforey	Marsannay-La-Côte	Communale	Nuits
Clos de la Marechale	Premeaux	Premier Cru	Nuits
Clos Arlot	Premeaux	Premier Cru	Nuits
Aux Perdrix	Premeaux	Premier Cru	Nuits
Aux Corvées	Premeaux	Premier Cru	Nuits
Les Forêts	Premeaux	Premier Cru	Nuits
Les Saint-Georges	Nuits-Saint-Georges	Premier Cru	Nuits
Les Poirets	Nuits-Saint-Georges	Premier Cru	Nuits
Les Pruliers	Nuits-Saint-Georges	Premier Cru	Nuits
Aux Bousselots	Nuits-Saint-Georges	Premier Cru	Nuits
Aux Boudots	Nuits-Saint-Georges	Premier Cru	Nuits
Les Terres Blanches	Premeaux	Premier Cru	Nuits
Aux Malconsorts	Vosne-Romanée	Premier Cru	Nuits
Les Chaumes	Vosne-Romanée	Premier Cru	Nuits
Les Suchots ouest	Vosne-Romanée	Premier Cru	Nuits
Les Suchots est	Vosne-Romanée	Premier Cru	Nuits

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Les Crâs	Vougeot	Premier Cru	Nuits
La Vigne Blanche	Vougeot	Premier Cru	Nuits
Les Sentiers	Vougeot	Premier Cru	Nuits
Les Milandes	Morey-Saint-Denis	Premier Cru	Nuits
La Perrière	Fixin	Premier Cru	Nuits
Clos du Chapitre	Fixin	Premier Cru	Nuits
Les Cazetiers	Gevrey-Chambertin	Premier Cru	Nuits
Lavaut	Gevrey-Chambertin	Premier Cru	Nuits
La Tâche	Vosne-Romanée	Grand Cru	Nuits
La Romanée	Vosne-Romanée	Grand Cru	Nuits
La Romanée Conti	Vosne-Romanée	Grand Cru	Nuits
Romanée Saint-Vivant nord	Vosne-Romanée	Grand Cru	Nuits
Romanée Saint-Vivant sud	Vosne-Romanée	Grand Cru	Nuits
Les Treux	Flagey-Échezeaux	Grand Cru	Nuits
Les Grands Échezeaux	Flagey-Échezeaux	Grand Cru	Nuits
Echezeaux du Dessus	Flagey-Échezeaux	Grand Cru	Nuits
Clos de Vougeot ouest	Vougeot	Grand Cru	Nuits
Clos de Vougeot est	Vougeot	Grand Cru	Nuits
Les Musigny	Chambolle-Musigny	Grand Cru	Nuits
Les Bonnes Mares	Chambolle-Musigny	Grand Cru	Nuits
Clos de Tart	Morey-Saint-Denis	Grand Cru	Nuits
Clos des Lambrays	Morey-Saint-Denis	Grand Cru	Nuits
Latricieres	Gevrey-Chambertin	Grand Cru	Nuits
Chambertin	Gevrey-Chambertin	Grand Cru	Nuits
Mazoyeres ou Charmes	Gevrey-Chambertin	Grand Cru	Nuits
Clos de Beze	Gevrey-Chambertin	Grand Cru	Nuits

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