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Precision Viticulture

Tools to measure and manage vineyard variability

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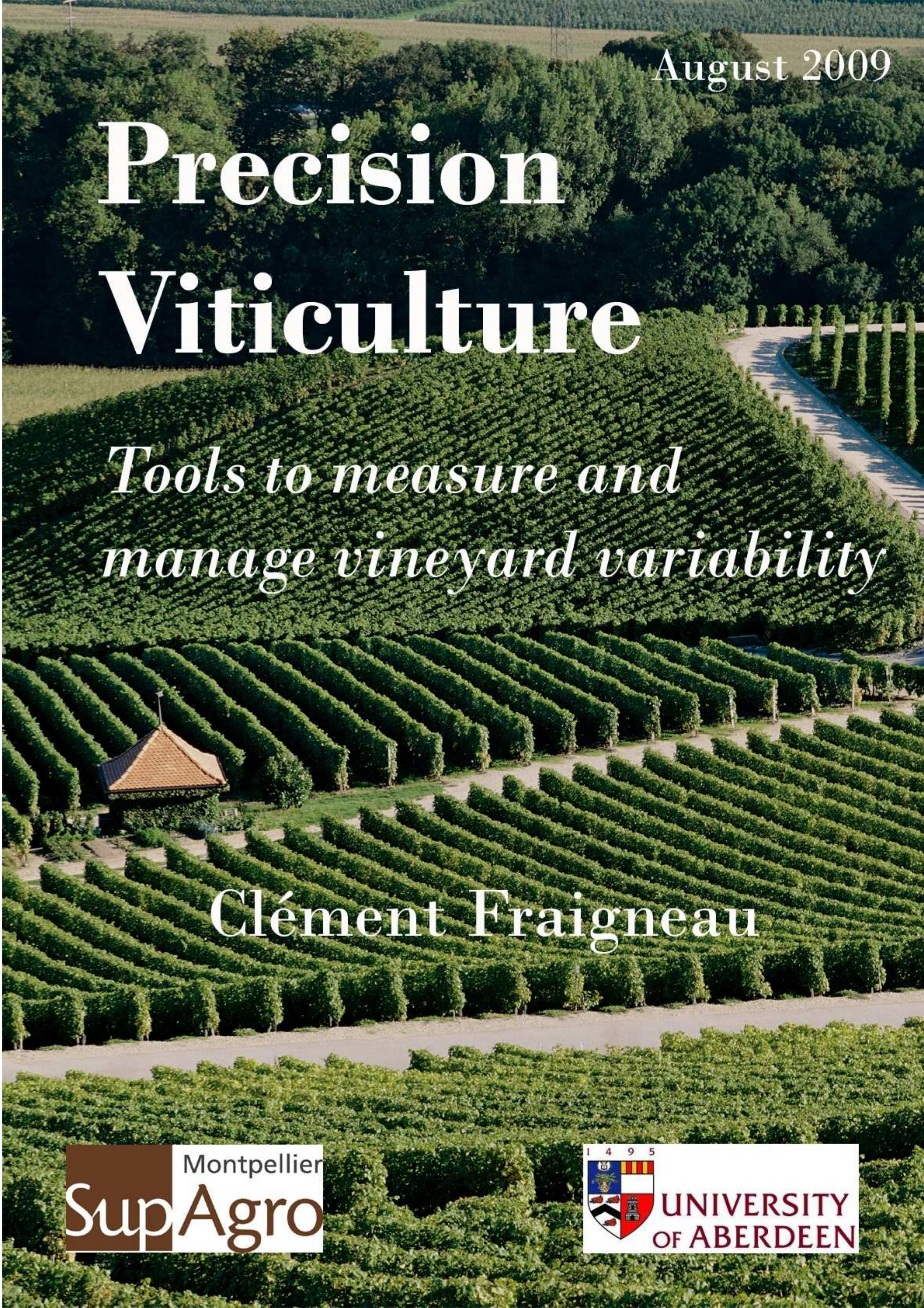

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Foreword and acknowledgements

This publication is the final report of a work placement realized by Clément Fraigneau (Montpellier SupAgro, France) at the department of Geography & Environment of the School of Geosciences (University of Aberdeen, UK), from June to August 2009. This paper provides a resume of the tools used in Precision Viticulture to measure and manage vineyard variability from previous researches. Information provided in this report is not exhaustive. All the references used are quoted.

All the figures in this report have been published before. All the references which contain these figures are quoted, and the commercial use of these figures is subject to royalties.

The author is especially grateful to David R. Green, Senior Lecturer and Director of the Marine Resource Management Degree Programme of the School of Geosciences (University of Aberdeen, UK), and supervisor of the work placement, and to Bruno Tisseyre, researcher at UMR ITAP (Montpellier SupAgro, France), and placement advisor, for their help and advice.

Contents

1. Introduction

Precision Agriculture (PA) is a concept growing for nearly twenty years. Viticulture, which is a very specific crop, follows this movement but with a bit delay. Indeed, Precision Viticulture (PV), which is the implementation of PA in vineyards, is a little harder to set up. The first problem is the specificity of the crop, which is perennial. Another problem is the traditions, mostly in France, and Europe in general. That is why PV is less developed in this continent than in new areas of production, such as California, Australia or New-Zealand.

Anyway, PV knows a great development for several years, due to an intensive research and to good relationships between research and winegrowers. Several studies show the economic viability of PV, and in a context of global warming and integrated plant protection, PV seems to be the way to be followed to better manage vineyards.

To do such a thing, researchers and winegrowers need tools, to measure and manage accurately the vineyards. These tools are numerous and evolve very quickly. Therefore, the aim of this paper is to provide a review of the tools available on the market. This report is divided into four parts. The first part defines PV and its specific terminology. Then, the second one refers to the essential tools of PV, such as Global Navigation Satellite Systems (GNSS), remote sensing images or Geographical Information System (GIS). Next, the third part provides a review of the existing tools: yield maps, canopy measurements (including vigour maps), soil measurements (including soil electrical surveys), quality measurements and mechanic tools. Finally, the last one mentions current research and future developments of PV.

2. Definition of Precision Viticulture

2.1. Definition of Precision Viticulture

The motto of Precision Viticulture could be: “Using knowledge of spatial variation to make better decisions”. Indeed, Precision Viticulture, or PV, is an approach of winegrape production which recognizes that the productivity of vineyards and individual blocks within vineyards can be inherently variable. Thus, vineyard management is targeted rather than implemented uniformly over large areas. Therefore the objective of PV is to gain increased control over inherently variable production systems such that any given management decision has an increased chance of delivering the desired or expected outcomes compared to conventional whole-of-paddock approaches to management (Bramley, 2001). PV can be seen as a cyclical process as shown in Figure 1.

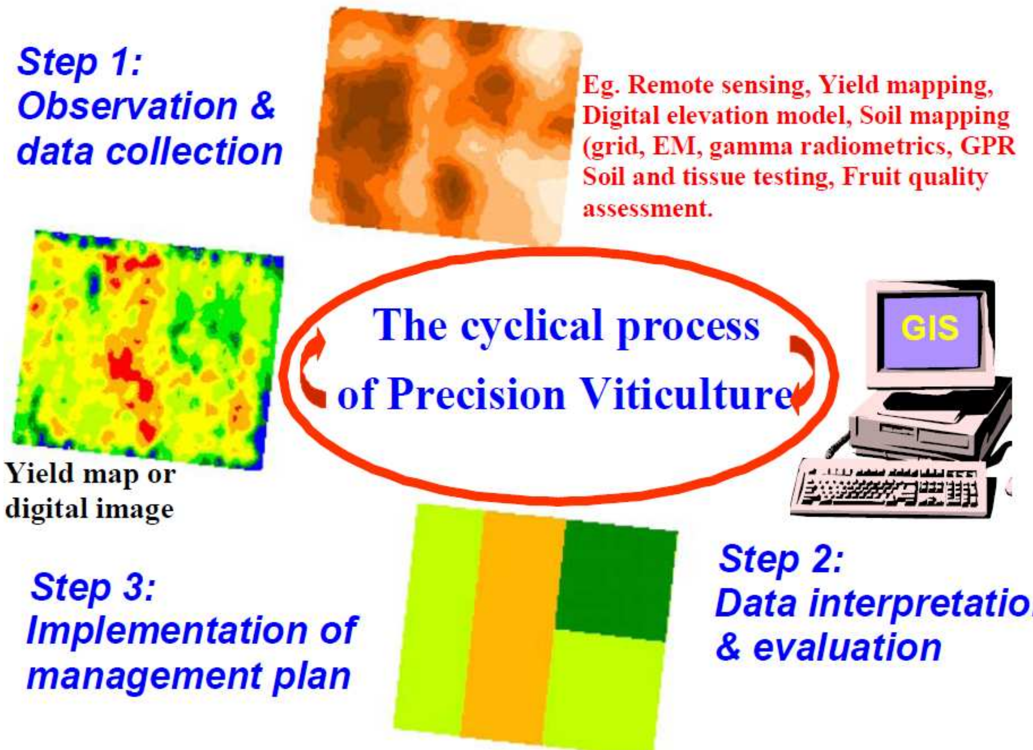


Figure 1: The three steps in the cyclical process of Precision Viticulture *(source: Bramley, 2001).*

Step one: Observation and data collection

Precision agriculture involves the collection of data describing the performance of the production system like yield or quality and the characteristics of the environment like soil properties at high spatial resolution. The type, timing and manner in which the data is very important because they have an appreciable effect on the interpretation of the results.

Step two: Data interpretation and evaluation

The interpretation of the data is a critical step as much care has to be taken. Geographical Information Systems (GIS) are very useful and often used.

Step three: Implementation of management plan

When relevant information is shown by the data interpretation, a management plan can be implemented. Then a vineyard is not considered as a block managed uniformly but several zones are determined with for example different yields. A differential management can be applied, such as a selective harvest. But steps one and three must often be repeated for a couple of years before implementing such a management plan.

2.2. Terminology

Differential management – the treatment of different zones of a single vineyard block in different ways.

Differential Global Positioning System – see Global Positioning System. A Differential Global Positioning System is an essential component of Precision Viticulture since it enables positional accuracy of approximately 1m through the use of differential corrections. These are adjustments to GPS position made on the basis of an additional signal received from a fixed, accurately surveyed location.

Electromagnetic induction meter – a type of sensor that measures the bulk electrical conductivity of the soil (referred to as the apparent electrical conductivity or EC_a).

Geographical Information System – a relational database with a mapping front end for the storage, analysis and display of spatially referenced data. It is an essential tool in spatial analysis.

Global Navigation Satellite System – a satellite-based navigation system which allows accurate positioning anywhere in the world

Global Positioning System – the most known Global Navigation Satellite System, created by the US Department of Defense for the US army.

Management zones – areas within a block of vineyard for which differential management is appropriate.

Multi-spectral sensing instruments – sensors which record electromagnetic information in a small number of separate wavebands (generally two to four) in the visible and near-visible

part of the electromagnetic spectrum. Used in remote sensing.

Normalised Difference Vegetation Index – a widely used indicator of plant biomass in agriculture. In viticulture, it provides a relative measure of canopy size and condition and therefore correlates with vigour. It is calculated from measures of reflected light at wavebands corresponding to red and infrared light.

Photosynthetically Active Biomass – a term used (in viticulture) to describe the photosynthetic potential of the vine canopy.

Pixel – the smallest unit of information on a map or image.

Plant Cell Density – a very used remotely-sensed indicator of vine vigour or canopy size. Like the Normalised Difference Vegetation Index, it is calculated from measures of reflected light at wavebands corresponding to red and infrared light.

Remote sensing – same as remote sensing but using equipment in close proximity to the target of interest, rather than far away as in remote sensing.

Radiometric resolution – the number of numerical steps available to each pixel to record brightness values.

Real-time kinematic differential Global Positioning System – a form of GPS where accuracies of about 2cm in all three dimensions (longitude, latitude, and elevation) can be obtained. When using this equipment, a local base station has to be set-up within a few kilometers from the site of interest.

Remote sensing – the detection and/or measurement of features on the earth's surface using sensors mounted on satellite or aircraft platforms. Its application in viticulture is at present generally confined to the inference of vigour and canopy condition.

Selective harvesting – the process whereby sections of a vineyard blocks are harvested separately and the fruit kept separate in the vineyard prior to delivery to the winery. Selective harvesting is a form of differential management.

Spatial data – information that is geographically located in space (i.e. geo-referenced) by a coordinate system (i.e. latitude and longitude in degrees, minutes and seconds, easting's and northing's in meters, elevation in meters). Spatial data may be in the form of points, lines, pixels or areas.

Spatial resolution – the on-ground accuracy of a map and/or intensity of on-the-ground measurement. This is closely related to the issue of scale. Thus, a 1:5000 map has a greater spatial resolution than a 1:100,000 map. Similarly a soil map derived from on-the-go EM38 survey has a higher spatial resolution than the one derived from a 75m grid.

Spatial structure – the "organization" of spatial data which results in its variation showing particular patterns. The ability to identify "management zones" within a vineyard depends on

the vineyard variation having some spatial structure as opposed to exhibiting random variation.

Spatial variation – variation in data values in space (as opposed to time). Spatial variation may be random and/or exhibit spatial structure.

2.3. Acronyms

BGR	Berry Growth Rate
DGPS	Differential Global Positioning System
DSS	Decision Support System
ECa	Apparent Electrical Conductivity
EGNOS	European Geostationary Navigation Overlay Service
EMI	Electromagnetic Induction
GIS	Geographical Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LAI	Leaf Area Index
MDG	Maximum Daily Trunk Growth
NDVI	Normalised Difference Vegetation Index
NIR	Near Infrared Reflectance
PAB	Photosynthetically Active Biomass
PCD	Plant Cell Density
PV	Precision Viticulture
RTK DGPS	Real-Time Kinematic Differential Global Positioning System
RVI	Ratio Vegetation Index
SSM	Site-Specific Management
SWP	Stem Water Potential
TDR	Time Domain Reflectometry
TOi	Technical Opportunity index
VES	Vertical Electrical Sounding
VRT	Variable Rate Technology

3. The fundamentals of PV

3.1. Geospatial technologies: Global Navigation Satellite Systems

One of the fundamentals of Precision Viticulture is to know exactly where we are within the vineyard. The Global Navigation Satellite Systems (GNSS), such as the most known, the Global Positioning System (GPS), are therefore essential. These systems use satellites to give a position in three dimensions: longitude, latitude and elevation. These tools are the basis to realize maps accurately, but the accuracy depends on what type of GPS is used. Three types of GPS exist.

Non-differential GPS

Non-differential GPS are GPS with an accuracy of several meters (Figure 2). At best, they only have an accuracy of 5 meter, so they are not the best tools to map vineyards. With such an error, it is difficult to have accurate datas.

Figure 2: Non-differential GPS *(source: http://www.magellangps.com/)*

Differential GPS

Differential GPS (DGPS) are GPS including a differential correction, and can have a sub-meter accuracy. Therefore, they are the best tools to make studies at the vineyard scale with a good accuracy. In Europe, since June 2006, a low cost technology of a differential correction can be provided: EGNOS (European Geostationary Navigation Overlay Service). This service allows a positioning accuracy of around 2m. Moreover, the arrival of new GNSS services, such as GALLILEO by the European Space Agency, is going to reduce the costs of this technology with more competition with the GPS (Tisseyre *et Al.,* 2007).

Real-time kinematic differential GPS

Real-time kinematic differential GPS, or RTK DGPS, are DGPS using a local base station whose coordinates are very well known. The accuracy of these GPS is very good: about 2cm. These types of GPS are mostly used to make elevation model or used to guide planting machines (Tisseyre *et Al.,* 2007).

3.2. Remote sensing images and the different resolutions

Remote sensing involves measuring features on the Earth's surface using remote satellite or aircraft-mounted sensors (Figure 3). In terms of optical remote sensing, sensors detect and record sunlight reflected from the surface of objects on the ground. The ability of a sensor to detect these objects is quantified in terms of the sensor's spatial, radiometric, spectral and temporal resolution.

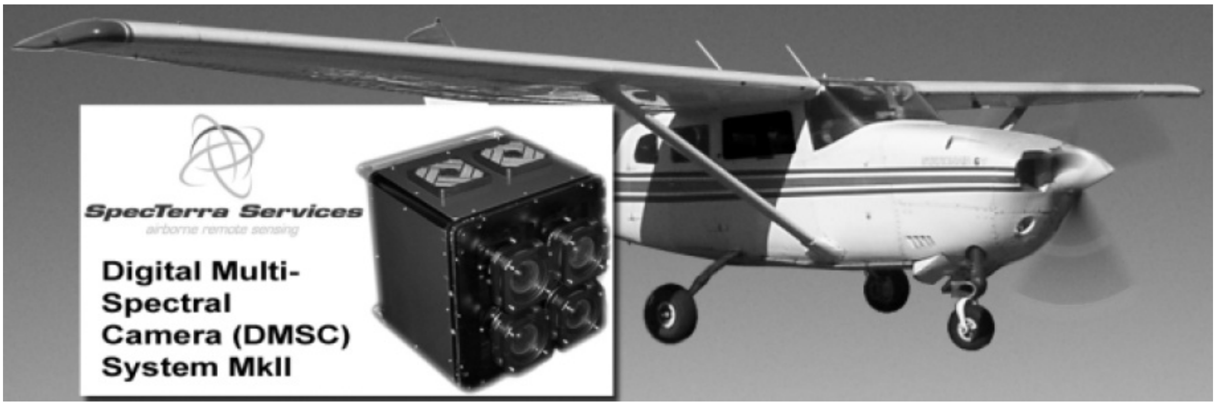


Figure 3: Cameras mounted underneath the aircraft with a computer on board which collects the data *(source: Proffitt, 2005)*.

3.2.1. Spatial resolution

Spatial resolution is a measure of the smallest object detectable on the ground. The number of available image-forming pixels in the sensor itself, and its distance from the ground, contribute to determining the pixel-size on the ground and the overall image footprint. For example, the American Landsat satellite, orbiting at a height of 705 km above the Earth's surface, is capable of recording images with a 30 m × 30 m pixel size (referred to as a 30 m pixel), and a footprint of 185 km × 185 km. The French SPOT satellite orbits 832 km above the earth's surface, generating full scenes of 60 km × 60 km and a 20 m pixel. This means that the smallest object that can be directly detected by the sensor is 30 m (Landsat) or 20 m (SPOT) in each dimension (Figure 4). More recently, high-resolution satellites such as IKONOS, which provides 4 m resolution multispectral imagery, have come on line, however, the cost of such data remains a significant impediment to its widespread use. Airborne sensors such as airborne digital cameras or video systems, which are flown up to 3 km above the ground, generally have 1 to 2 m pixels and corresponding image footprints of the order of 100 ha (Figure 5). Figures 4 and 5 illustrate that while Landsat and SPOT satellite imagery, with spatial resolution of the order of tens-of metres, is suitable for applications requiring regional coverage, the pixel size precludes its use in the investigation of targets of the size of typical vineyard blocks, and of features that may vary within vineyards (Hall *et Al.,* 2002).

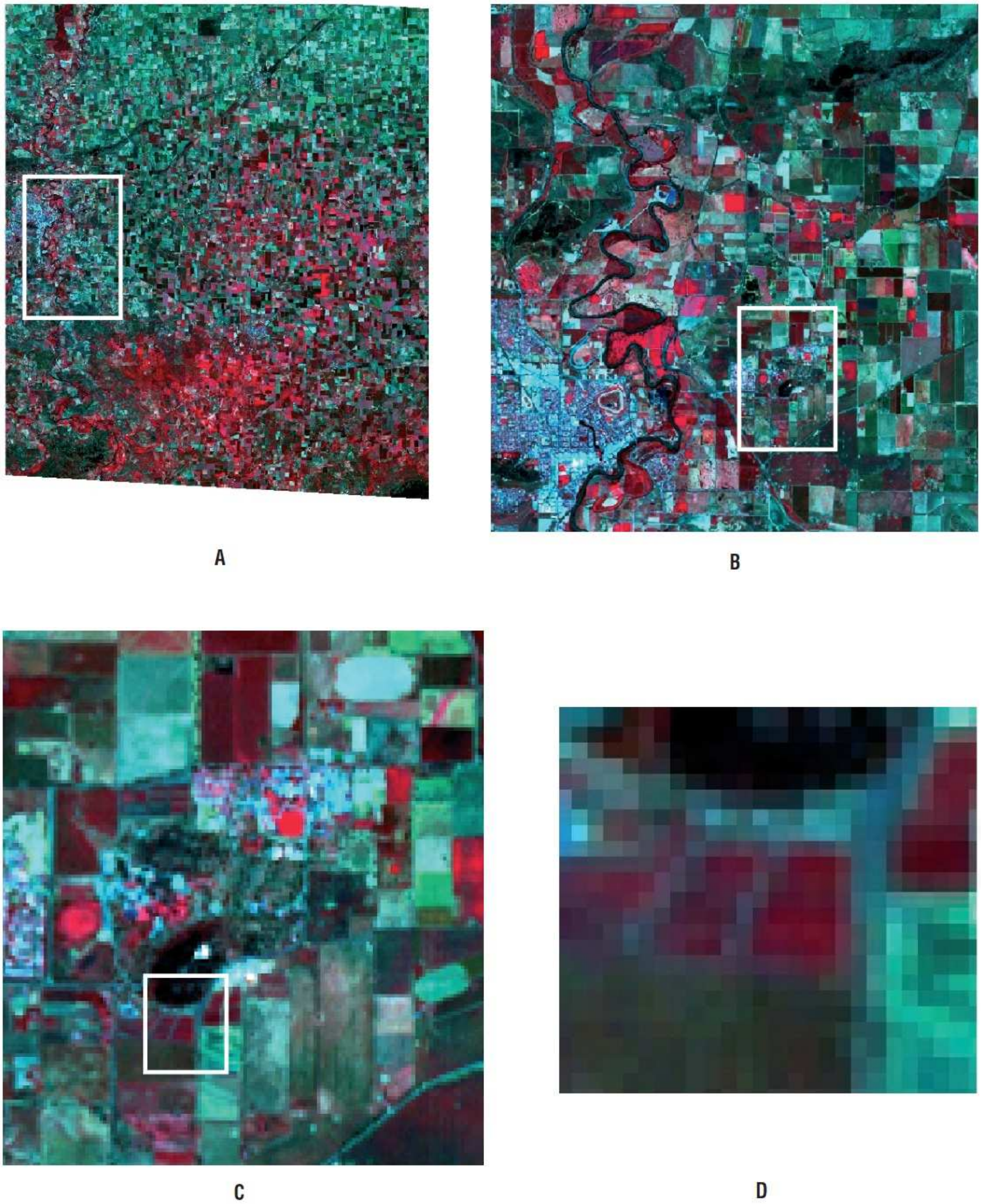


Figure 4: A typical commercial satellite image (French SPOT) of the Wagga Wagga region, SE NSW, acquired on October 1998. Pixel size = 20 m. (a) 60 km × 60 km full scene. (b) magnified, 13 km × 13 km, sub-scene of Wagga Wagga. (c) magnified, 3 km × 3 km, sub-scene of Charles Sturt University Wagga Wagga Campus. (d) magnified, 400 m × 600 m (24 Ha), sub-scene of Charles Sturt University Vineyard Stage IIA *(source: Hall et Al., 2002).*

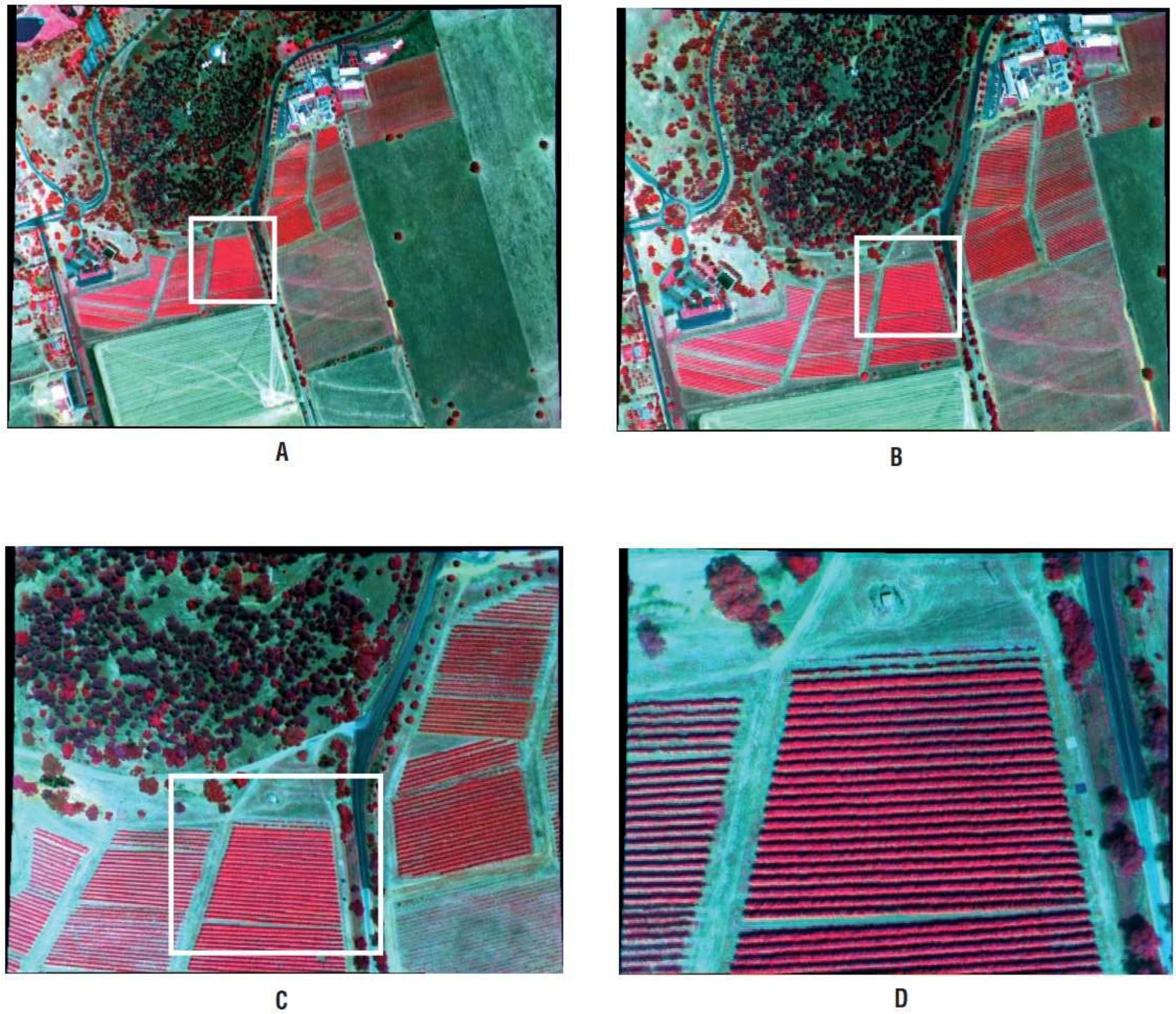


Figure 5: Multispectral airborne images (false-colour) of Charles Sturt University Wagga Wagga Vineyard acquired in January, 2001. (a) Altitude = 2.25 km, pixel size = 1.5 m, area coverage = 110 Ha. (b) Altitude = 1.5 km, pixel size = 1.0 m, area coverage = 49 Ha. (c) Altitude = 750 m, pixel size = 50 cm, area coverage = 12 Ha. (d) Altitude = 300 m, pixel size = 20 cm, area coverage = 2 Ha. Note, this is the same site as depicted in Figure 1 (d) *(source: Hall et Al., 2002).*

3.2.2. Radiometric resolution

Radiometric resolution specifies the number of discrete radiometric levels available to individual pixels to record the intensity of measured radiation from a target in a given waveband. For example, 8-bit radiometric resolution means there are 28 = 256 levels available (0 = darkest, 256 = brightest) while 10-bit sensors have 210 = 1024 levels available to each image pixel. (Hall *et Al.,* 2002).

3.2.3. Spectral resolution

The spectral resolution is the number of wavebands of data that can be simultaneously recorded at each pixel. The amount of sunlight reflected off a target is described in terms of the target's reflectance profile. All photosynthesising plants, including vine canopies and cover crops, do not reflect much light in blue or red wavelengths because chlorophylls (and related pigments) absorb much of the incident energy in these wavelengths for the process of photosynthesis. However, these targets reflect a higher proportion of light in the green wavelengths, again due to chlorophylls and related pigments, and this is why such foliage appears green when viewed by the human eye. However, in the near-infrared wavelengths (wavelengths greater than about 700 nm), photosynthesising plants reflect large proportions of the incident sunlight (in excess of 65%). These wavelengths, to which the human eye is insensitive, can be detected by appropriate instruments. The amount of sunlight reflected in these wavelengths is very sensitive to leaf cell structure and this is influenced by water content. Figures 6 (a) and (b) show the reflectance profile of a typical vegetated target. Superimposed on these profiles is a set of wavebands corresponding to the sensitivity of a hypothetical instrument and the reflectance profile that would be inferred from the response of that instrument to the ground target. In Figure 6 (a), the hypothetical instrument measures the spectral signature of the target in four wavebands. While an accurate measure of the target reflectance would be extracted at the four specified wavebands, the shape of the reflectance profile of the vegetated target is only poorly described. Using thirteen closely spaced wavebands (Figure 6 (b)), the reflectance of the target is recorded for each waveband and the shape of the entire spectral profile is more accurately described. In an application where fine detail in the shape of the spectral profile is required, the higher spectral-resolution instrument (Figure 6 (b)) would be appropriate (Hall *et Al.,* 2002).

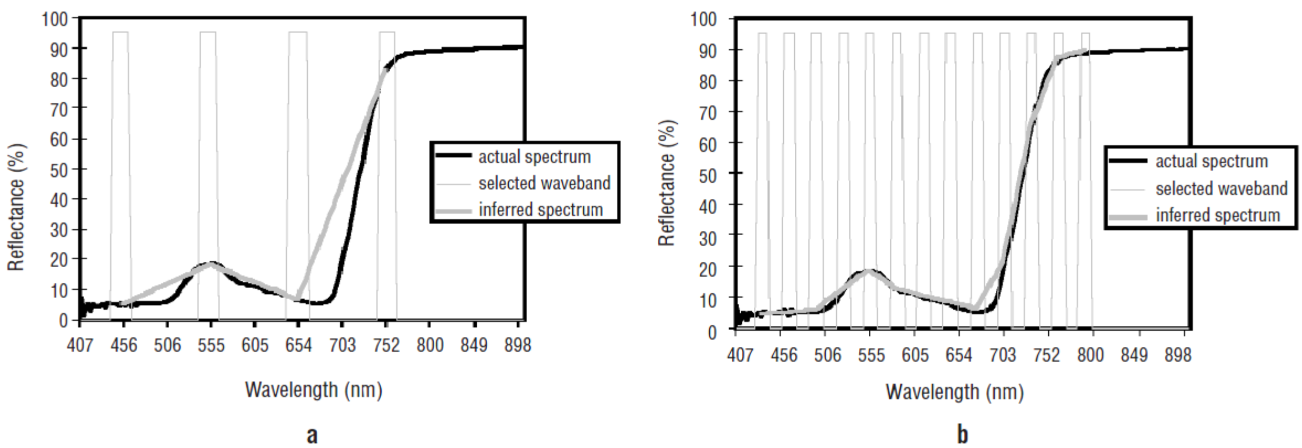
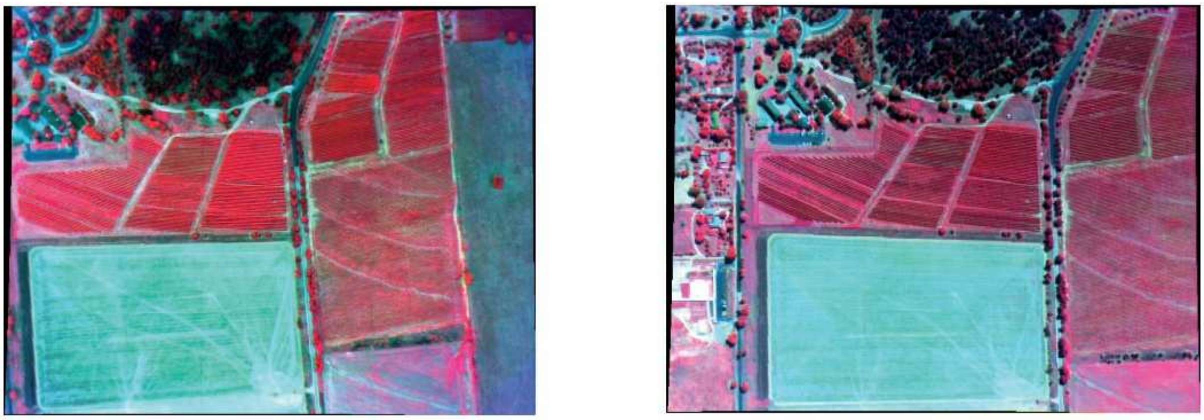


Figure 6: Comparison between an actual vegetation reflectance profile and an inferred reflectance profile using (a) 4 wavebands (multispectral), and (b) 13 wavebands (hyperspectral) ***(source: Hall et Al., 2002).***

3.2.4. Temporal resolution

When using any sensor for commercial monitoring or management purposes, it is important to consider how often to collect images (revisit frequency or temporal resolution). Typical commercial satellites like the American Landsat and French SPOT satellites have revisit intervals of 16 and 26 days, respectively. In the case of SPOT imagery, a target-pointing capability during different overpasses could reduce this interval to as low as 2 days. Aircraft-mounted sensors, on the other hand, can theoretically be operated at any time, and have the advantage of being able to operate under a high-cloud base (Figure 7). (Hall *et Al.,* 2002).



A B

Figure 7: Airborne sensors are operationally more flexible compared to satellites. For example, cloud cover precludes the use of satellite imagery. Multispectral airborne image (false-colour) of Charles Sturt University Wagga Wagga Vineyard acquired late February, 2001 under (a) full cloud-cover with cloud-base at 2.4 km, imaging altitude = 1.5 km, pixel size = 1.0 m, (b) clear skies, imaging altitude = 1.5 km, pixel size = 1.0 m. Note the absence of shadows in (a), while in (b) the shadows enhance the contrast between individual objects such as trees and vine rows. This is the same site as depicted in Figures 5 (d) and 6 *(source: Hall et Al., 2002).*

3.3. Geographical Information Systems and data management

A Geographical Information System (GIS) is a computer software which permits the storage of spatially referenced data acquired on the field in a database, and which can analyze and display them. The use of GIS is essential in Precision Viticulture. Numerous software are available on the market:

- Open source software such as GRASS, Quantum GIS or gvSIG.
- Commercial software such as Arc GIS or Mapinfo.

3.4. Vine growth stages

The knowledge of vine growth stages is very important for all the fieldworks in PV because some measurements have to be done at specific vine growth stages.

The measurement consists in noticing the vine growth stages in the vineyard, that is to say the phenology stages of the vine. No specific equipment is necessary, you have just to know the different growth stages of the vine. A differential GPS (DGPS) can be used if we want to show the difference of phenology stages within a vineyard, but these studies are often made at a bigger scale (Mariani *et Al.*, 2007). The measurement is easy. You have to recognize the different vine growth stages and note down them. Vine growth stages are divided into 47 stages, as shown in figure 8. Photographs can also be used, as shown in figure 9. Using a DGPS, you have to note down the place where the observation was made.

The measurement takes a few seconds per replicate if you know well the different stages, a bit more if you have to look into a document like Figure 8. Some measurements into a vineyard are sufficient to characterize the growth stage if you don't use a GPS, otherwise a greater sampling has to be done. Vine growth stages should be recorded when each other measurement is taken.

The knowledge of the grapevine phenological course is an essential base for any provisional model for the estimation of potential yield and quality.

This measurement shows also the different effects of weather conditions. Stressing factors as spring frost, rain shortage or excess, low or high temperature, may have very different effects, in relation to the phenological phase. On the other side, good weather conditions may have an effect on vine yield and grape quality potential, only if they match a specific and critical phenological phase, like flowering or the end of grape ripening (Mariani *et Al.*, 2007).

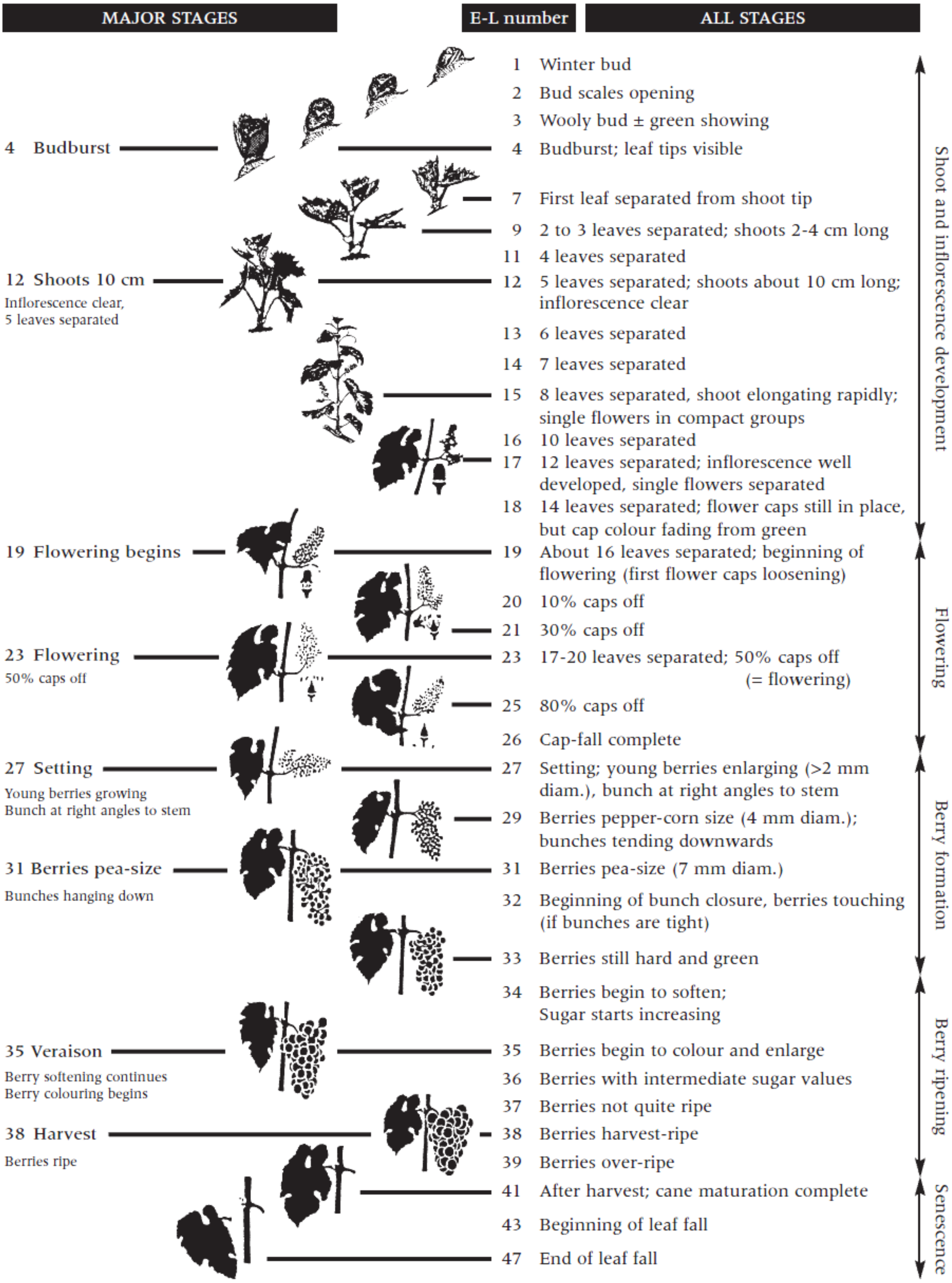


Figure 8: Diagram of the vine growth stages *(source: Dry et Al., 2004).*

Stage A or Stage 01

Winter bud
Vine eye of the previous year, almost entirely covered by two brownish protective scales.

Stage B or Stage 03

Wooly bud
Vine eye swollen, scales move apart.

Stage C or Stage 05

Green showing
Vine eye keeps swelling and becomes longer. It gets green colour.

Stage D or Stage 06

Leaves leaving
Appearance of rudimentary leaves collected in a rosette.

Stage E or Stage 09

Leaves separated
First leaves totally separated. Shoot visible clearly.

Stage F or Stage 12

Inflorescence clear
Rudimentary clusters appearing at the shoot. Four to six leaves unfolded.

Stage G or Stage 15

Single flowers in compact group
Clusters space out on the shoot. Floral organs still agglomerated.

Stage H or Stage 17

Single flowers separated
The buds are clearly isolated. Appearance of the typical form of the inflorescence.

Stage I or Stage 23

Flowering
Caps stand out at the base and fall, the stamens and pistil are visible.

Stage J or Stage 27

Setting
Pistil begins to swell. Wilted stamens often remain attached to their base.

Stage K or Stage 31

Berries pea-size
The berries have a pea-size. Bunches are hanging.

Stage L or Stage 33

Bunch closure

Stage M or Stage 36

Veraison
Berries are lighting or coloring.

Stage N or 38

Berries harvest-ripe
Berries are ready for vintage.

Stage O or 43

Beginning of leaf fall

Figure 9: Photographs of the different vine growth stages with name of stages according to Baggiolini (letters) and to Eichhorn and Lorentz (numbers) ***(source: Institut Français de la Vigne et du Vin, www.vignevin-sudouest.com).***

4. The tools of Precision Viticulture

4.1. Yield monitoring

4.1.1. Yield monitors

Yield is an important measurement for the winegrower. That is why several yield monitors has been developed for a few years. At the moment, there are three yield monitors commercialized (Tisseyre *et Al.*, 2007). These yield monitors consist on an apparatus which measures the quantity of grapes harvested by the harvester, with a DGPS measuring the coordinates of this measurement. There are two types of yield-monitoring system, which are both non-intrusive so the measurement doesn't disturb the harvest (Proffitt *et Al.*, 2006):

- The sonic beam yield-monitoring system: it uses ultra-sonic sensors to measure a volume of grapes which is flowing along the discharge conveyor.
- The gravimetric yield-monitoring system: it weighs the grapes flowing across load cells fitted below the discharge conveyor belt of the harvester (Figure 10).

Both systems are quite accurate but need to be calibrated. The calibration is made after the measurement: the weight of grapes recorded by the yield-monitoring and the weight received by the winery are compared, and a correction is applied if there is a difference.

Figure 10: Equipment required to record yield. (a) GPS antenna mounted on the harvester. (b) Computer in the tractor to collect and to view data. (c) Gravimetric yield-monitoring system with a weigh platform positioned under the conveyor belt *(source: Proffitt, 2005).*

4.1.2.Yield maps

With these pieces of information recorded by the system, including the coordinates calculated by the DGPS, we can easily produce yield maps. The yield monitors can record about 2000 measurements.ha^{-1} with an average speed of 3 km.h^{-1} (Tisseyre *et Al.*, 2007), so very accurate maps can be obtained. The use of yield monitoring remains specific to large

vineyards and big wineries, in Australia, Spain or California. In France, this kind of management remains marginal.

Bramley *et Al.* (2001) gave the steps to be followed to correctly realize yield maps. Figure 11 shows a yield map obtained after interpolation. The measurements are made in the raw, and the raw points are shown as black dots in the figure.

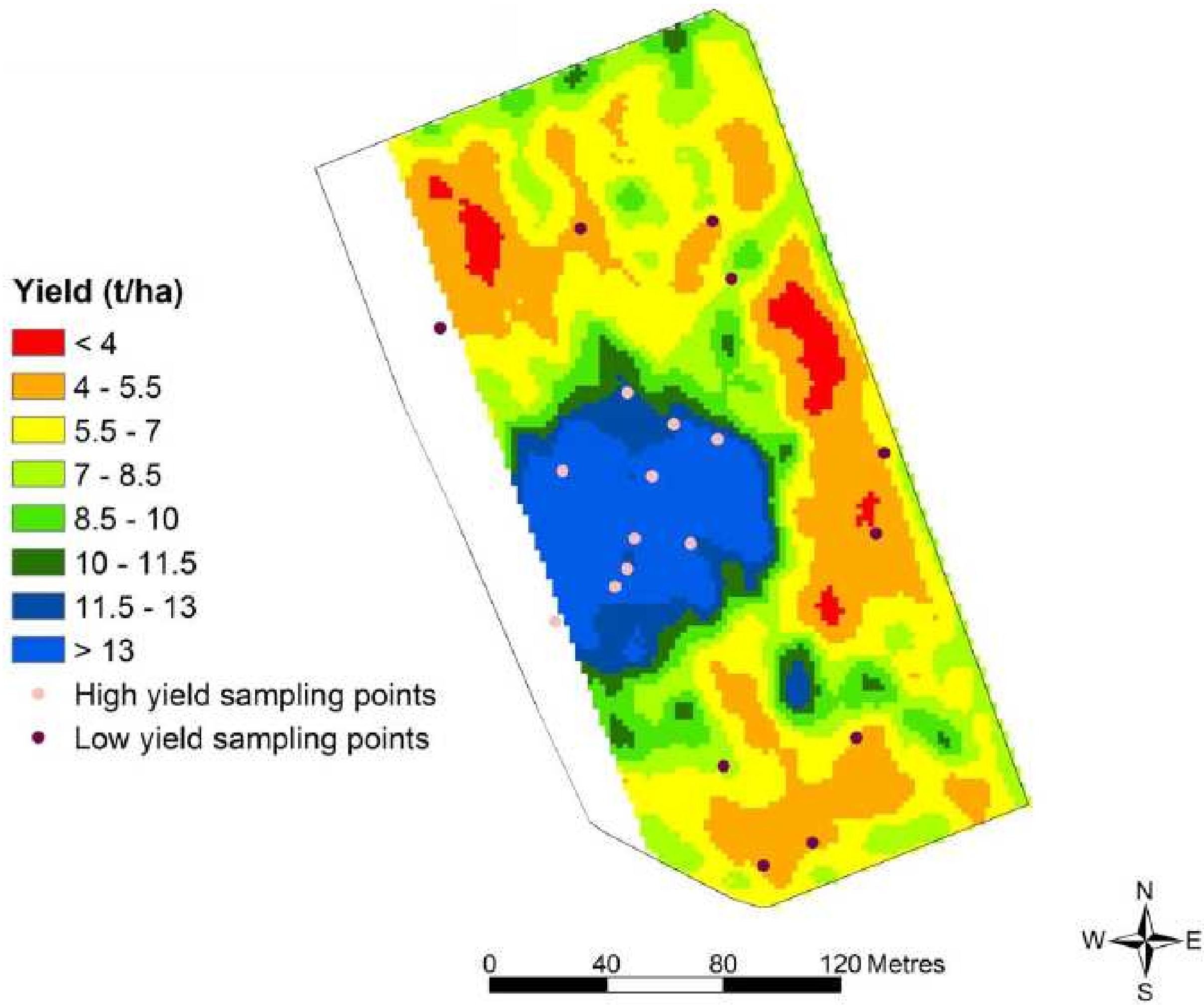


Figure 11: Yield measured in a vineyard at harvest in Padthaway, Australia, 1999 ***(source: Bramley, CSIRO).***

4.1.3. Selective harvesting

Yield maps as above are not very relevant to define zones where a winegrower could make different managements. Tisseyre *et Al.* (2008) propose a Technical Opportunity index (TOi) to see if a site-specific management (SSM) is possible from a yield map.

Figure 12 shows that SSM is not possible in all the fields. In field (c) two zones can be clearly identified, whereas in field (a) it is impossible to apply a SSM, even if the variability within the field is maybe the same as in field (c). The index proposed permits to know if a SSM can be applied. This mathematical tool, that needs to be furthered, is a good index to help with selective harvesting.

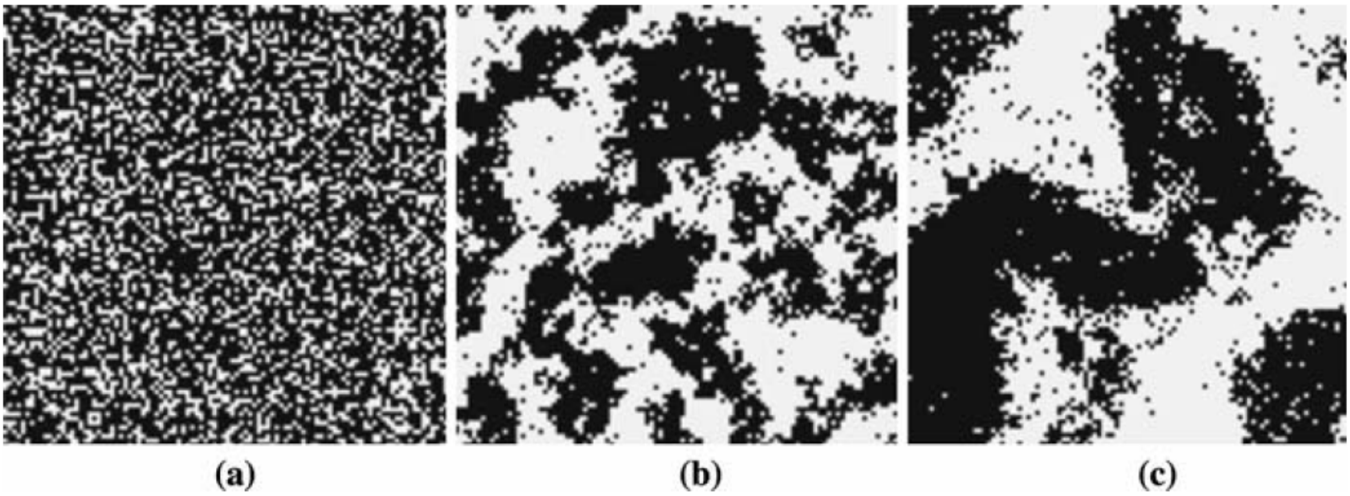


Figure 12: Three hypothetical fields after application of a threshold to the within-field data *(source: Tisseyre et Al., 2008).*

4.2. Canopy measurements

4.2.1. Vigour map using remote sensing

Infrared aerial photography

Usually, people think that aerial photography is just an image as we could see on a plane. But human eye cannot see everything, it can see only visible light. As shown in Figure 13, the reflectance of a plant, such as vine, depends on the wavelength. The reflectance is very high for wavelength of 800 nm, which corresponds to near infrared (NIR). We can see also in this graph that the reflectance of the bare soil is not as high as vine one at this wavelength. Therefore, taking photographs with a NIR waveband could help to differentiate the vine to the soil. Moreover, the more the plant will be active, the higher the reflectance will be, that is to say that we will be able to differentiate low and strong vigour zones within the vineyard. The best time to acquire imagery is at veraison.

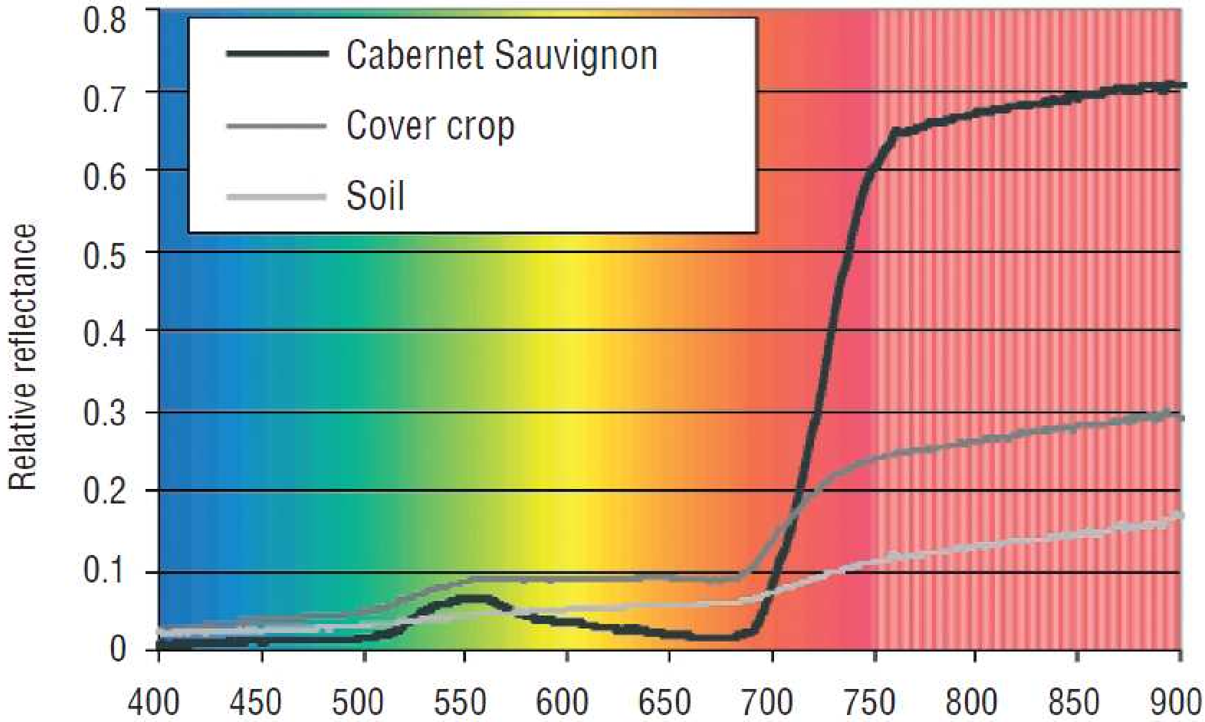


Figure 13: Spectral reflectance profiles for Cabernet Sauvignon, cover crop (chick-peas) and exposed redbrown soil. (Percentage of reflected sunlight = 100 × Relative reflectance). Data acquired from Charles Sturt University's vineyard in Wagga Wagga, NSW *(source: Hall et Al., 2002).*

Use of vegetation indices

The difference on the images shown thanks to the NIR waveband has to be quantified mathematically. In Precision Viticulture, two indices are used (Hall *et Al.,* 2002):

- **The Normalised Difference Vegetation Index (NDVI)**

  The NDVI is calculated thanks to the formula:

$$\text{NDVI} = \frac{\text{NIR}-\text{Red}}{\text{NIR}+\text{Red}} \text{ (formula 1)}$$

  NIR and Red are the respectively the reflectances of the NIR and the Red wavebands. With this index, we can differentiate vine, whose NDVI is high, from soil, whose NDVI is close to zero. Then NDVI maps can be obtained as shown on Figure 14. Applications of NDVI are limited in regions with high plantation density (> 6,000 ha^{-1}) and with shoots in vertical position: the canopies are narrow, and remote sensing is not the most effective way to measure the vigour of the vine (Tisseyre *et Al.,* 2007).

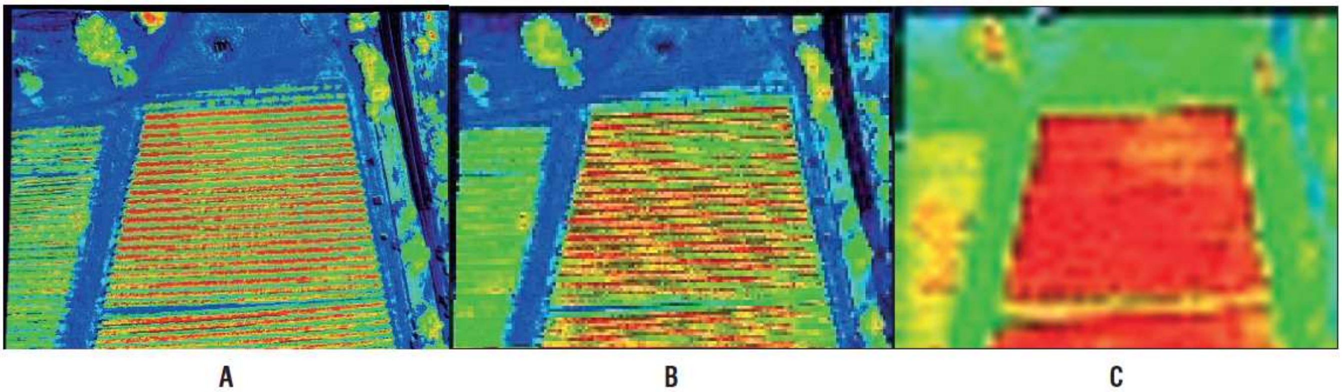


Figure 14: NDVI images of a Cabernet Sauvignon block with different spatial resolutions. (a) 20 cm, (b) 1 m, and (c) 3m. Vine row spacing = 3 m. Extracted from *Lamb et Al.* (2001).

- **The Plant Cell Density (PCD) or Ratio Vegetation Index (RVI)**

  The PCD or RVI is calculated thanks to the formula:

$$\text{PCD or RVI} = \frac{\text{NIR}}{\text{Red}} \text{ (formula 2)}$$

With this index, we can differentiate areas with a high photosynthetically active biomass (PAB) which have a high PCD, from areas with low PAB which have a low PCD. PCD maps can be made, as shown in Figure 15.

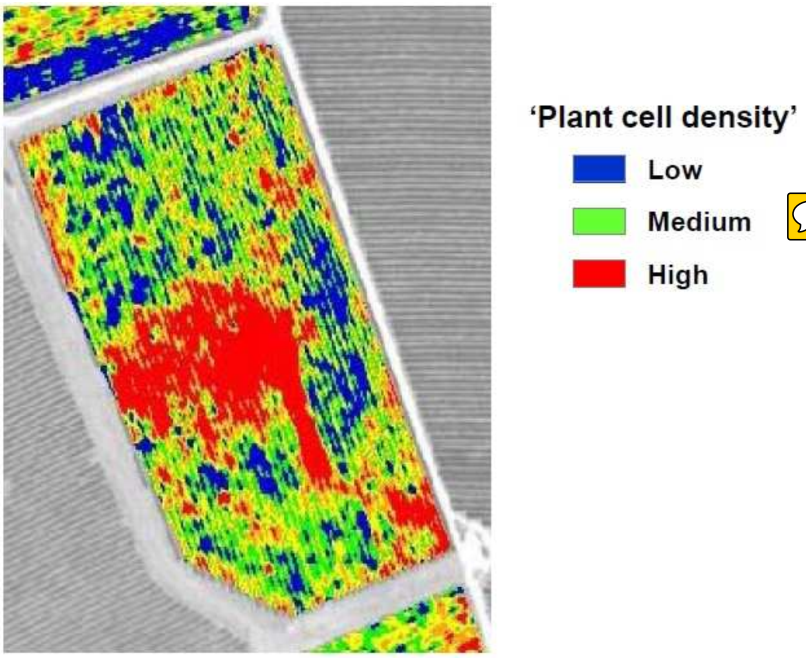


Figure 15: PCD calculated from an image in a vineyard at veraison in Padthaway, Australia, 2001 *(source: Bramley, CSIRO).*

The problem of the inter-row

What is important with these two indices is the resolution of the image. Hall *et Al.* (2002) found that these indices were interesting within a vineyard only with a submeter resolution. With a 20 cm resolution for example, we can eliminate the inter-row space, so only the NDVI of the vine is calculated. Hall *et Al.* (2003) developed an algorithm, named "Vinecrawler" to identify individual vine rows and extract sets of reflectance at quasi regular distances (approximately one pixel length) along the rows. With this algorithm, which is useful only when using high-spatial-resolution aerial multispectral images, very accurate maps (as the one in Figure 16) can be produced.

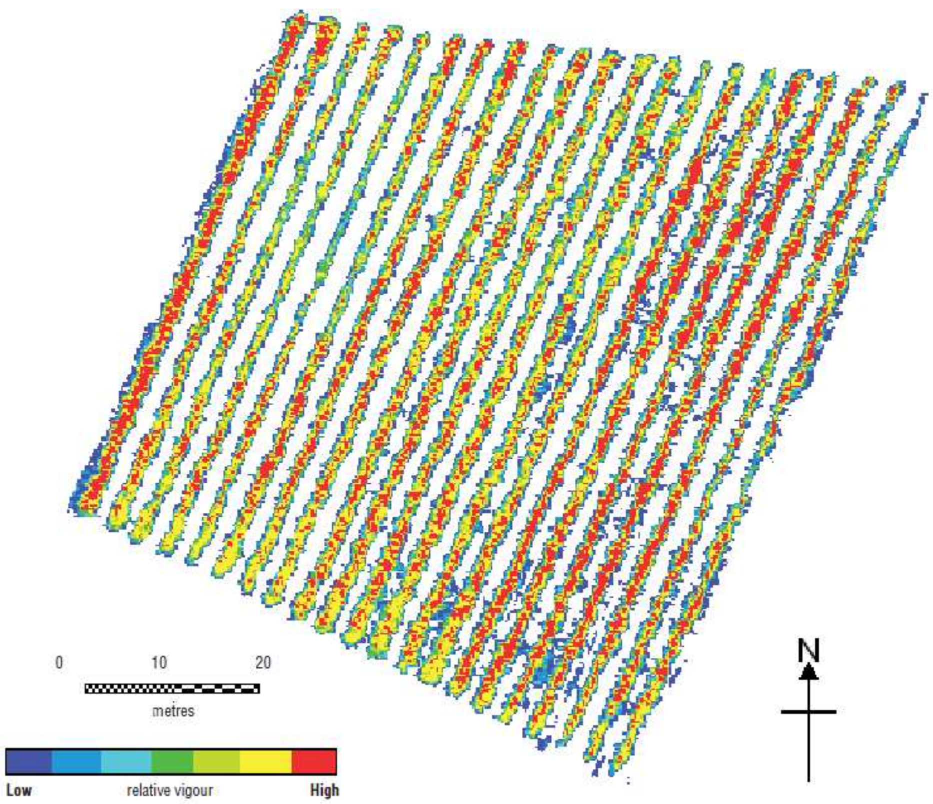


Figure 16: Colour-coded NDVI image of CSU vineyard with fully developed canopy, January 1999. With the inter-row space eliminated, this image conveys a useful indication of vine PAB (PAB embodies both vine size and photosynthetic potential) ***(source: Hall et Al., 2002).***

4.2.2. Ground-based monitoring systems

As the use of indices calculated from aerial images as NDVI or PCD is not relevant in vineyards with high plantation density (> 6,000 h^{-1}) and with shoots in vertical position, ground-based monitoring systems have also been developed to assess and to map canopy properties. Most of these systems are based on a digital imaging system which allows the measurement of several parameters such as canopy height and canopy porosity and can be mounted on vineyard machinery used for trimming or spraying, and the measurements can be done several times during the developing season to better manage the vineyard (Tisseyre *et Al.,* 2007).

A pink screen (Figure 17) can be used to measure precisely the canopy porosity: the row behind the one that we want to measure is hidden by this screen (Tuohy, 2005).

(a) (b)

Figure 17: (a) Pink screen mounted on a four-wheel motorbike to make ground-based measurements. (b) Photograph of a row taken with the pink screen placed behind the row *(source: Tuohy, 2005).*

4.2.3. Canopy density

The measurement of the canopy density is done with an apparatus which measures two indexes: Photosynthetically Active Radiation (PAR) and Leaf Area Index (LAI).The equipment used can be a ceptometer, such as the AccuPAR model LP-80 (Figure 18). This model is a linear PAR ceptometer consisting of an integrated probe and microcontroller. The probe is about 86.5cm long and contains 80 sensors that are sensitive to the PAR waveband. The microcontroller interprets the PAR signals coming from the probe, allowing you to read PAR. It also calculates LAI of the samples instantly with each PAR measurement you take, using the intercepted and available PAR and other variables.

Figure 18: Ceptometer (AccuPAR model LP-80) ***(source : http://www.ictinter national. com.au).***

With a real-time measurement apparatus such as the AccuPAR model LP-80, as soon as the ceptometer is on, you're measuring PAR in the PAR sampling mode. Real-time PAR values are displayed on screen, and can be stored with the press of a button. Simply take one PAR reading above the canopy and one below it, and an LAI calculation is displayed. With each subsequent measurement, this value is updated and displayed on the screen. The measurement in real-time takes a few seconds per replicate. The canopy density measured with a ceptometer is usually taken in veraison or just before the harvest.

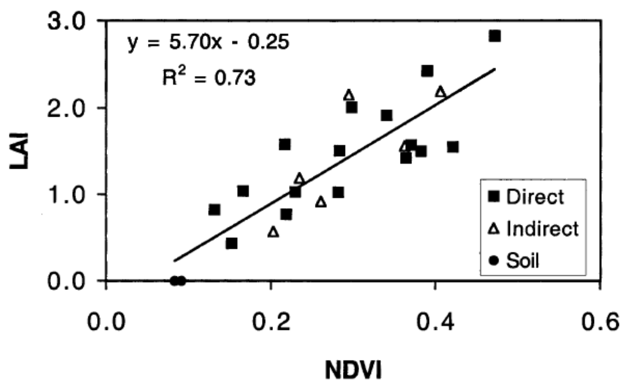


Figure 19: Image-based NDVI vs. ground-based LAI measurement. Sites of direct and indirect LAI measurement as indicated. Points with zero LAI represent bare soil ***(source: Johnson et Al., 2003).***

Vineyard leaf area is a key determinant of grape characteristics and wine quality. Johnson *et Al.* (2001 & 2003) found very interesting relationships between LAI and NDVI, with $r^2 = 0.73$ (Figure 19). Other indices such as Leaf Area per simple vine (LAv, see 4.2.4.) calculated from LAI measurements can also be used and offer good relationships with indices as NDVI.

4.2.4. Pruning weight

The measurement consists in weighing the canes cut after the pruning to estimate the vine vigour. A simple top-load scale can be used (Figure 20), with a DGPS to know the coordinates of the sample measured.

Figure 20: Top-load scale weighing canes *(source: Kaan et Al., 2006).*

The operating principle is very easy: you have just to weigh and note down the canes pruning from a same vine, and note down the coordinates of this vine. The measurement takes a few minutes per replicate. The survey spacing is determined by the level of detail required. For a 10 metres survey, a diameter trunk should be measured every 10 metres in a row, and every third row should be measured in an established vineyard with 3 metres row spacings. This measurement can be done only in dormancy, when the pruning is made.

Johnson *et Al.* (2003) found a good relationship between pruning weight and natural logarithm of LAv, with $r^2 = 0.63$. LAv is the leaf area (m^2) per sample vine and can be calculated with the formula:

$$LAv = W_t * SLA \quad \text{(formula 3)}$$

W_t is the total weight (g) and SLA the specific leaf area (m^2 leaf area.g^{-1} fresh weight).

With LAv, we can calculate LAI (Leaf Area Index), which is a very useful index, with the formula:

$$LAI_v = \frac{\text{LAv}}{\text{vine area}} \quad \text{(formula 4)}$$

Dobrowski *et Al.* (2003) have demonstrated that there was a good relationship between pruning weights and Ratio Vegetation Indices (RVI) calculated from aerial photos. A good relationship was previously found between RVI and vineyard canopy densities. As pruning weights measurements are easier to take than canopies densities, this could be very interesting to manage the vineyard early in the season. For example, if an area is detected thanks to aerial images where pruning weights are expected to be low (<0.5 kg/m of canopy), which would likely mean insufficient vegetation to ripen the fruit. We could take immediate action with crop thinning, or N applications to boost growth.

4.2.5. Trunk diameter

Trunk diameter of the vine is an useful measurement to evaluate the grapevine water status.

The diameter of the trunk can be measured with a calliper. Two types of caliper exist: the first one is a vernier calliper, with a 1/10 millimeter accuracy. The second one, as shown in Figure 21, is a digital calliper, which can have an accuracy of 1/100 millimeter. This tool is the less expensive way to take the measurement within the vineyard with a good accuracy, but it doesn't allow the measurement of the trunk growth each day. The use of this tool is relevant only to map a vineyard, and see high or low vigour zones within this vineyard. Figure 22 shows a NDVI map and a trunk circumference map. We can see similar patterns on the both maps. For example, the North area is a low vigour zone low according to NDVI, and corresponds to a low trunk circumference zone.

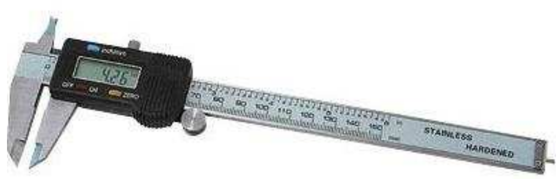


Figure 21: Digital calliper *(source: http://nextday.diy.com).*

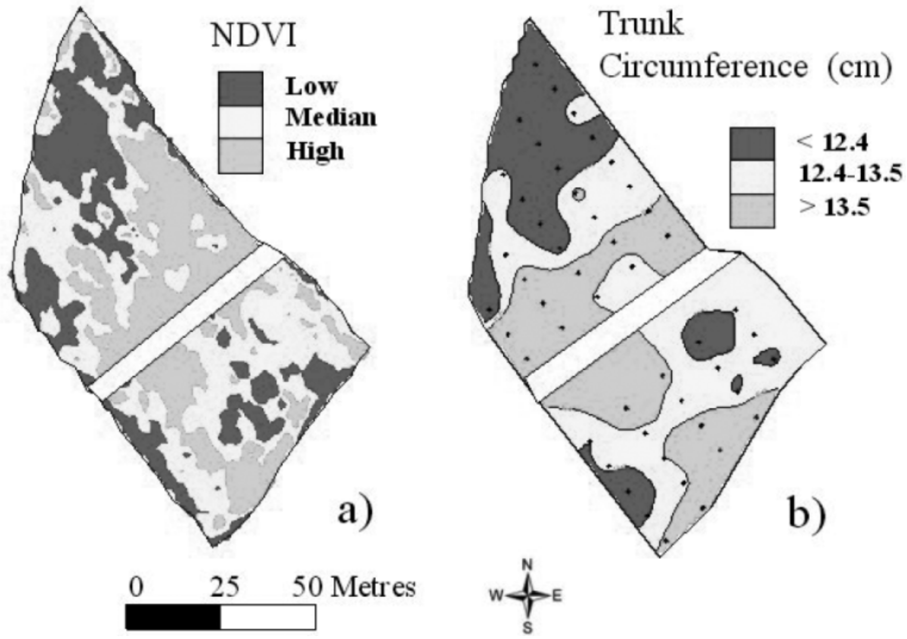


Figure 22: A 1.2 ha vineyard of Syrah grapes in the Clape Massif, Southern France. a) 3 class NDVI map derived from 1 m resolution aerial imagery. b) 3 class map of trunk circumference (cm) created by inverse weighting distance interpolation. The actual measurements points are shown as black dots in the figure (n = 49) *(source: Tisseyre et Al., 2007).*

Another way to measure the trunk diameter is to use a dendrometer. This electronic measuring apparatus, fixed around the trunk as shown in Figure 23, measures the diameter with an accuracy of 1/100 millimeter. Moreover, this tool can be used wireless. But this apparatus is more expensive : around $650. Therefore, there are often only one or two apparatus within the vineyard. The measurement is easy but has to be done always at the same high of the trunk (20 or 30 centimetres below the first branch for example). It is automatic and can be done several times per day.

Figure 23: Dendrometer *(source : http://www.ictinternational.com.au).*

This measurement can be done at all vine growth stages, from dormancy to post-harvest, but it is more interesting to do it from 20 to 30 days after bud brake to veraison.

When veraison begins, trunk growth rate stoppes or decreases whatever the grapevine water status (Selles *et Al.*, 2007). The use of some indices is useful to find correlations between trunk diameter and grapevine water status. Average maximum daily trunk growth (MDG) for example is clearly related with soil water content from berry set to veraison with $r^2 = 0.49$ (Selles *et Al.,* 2007). Moreover, there is a good relationship between average MDG and average berry growth rate (BGR) from fruit set to veraison. This means that, in this period, the faster the trunk growth, the faster will be the growth of the berry, and a bigger berry size will be obtained at harvest. On the other hand, Stem Water Potential (SWP) measured at midday is well related with irrigation treatments. A good relationship was also found between SWP and BGR from fruit set to veraison ($r^2 = 0.53$). However MDG is more sensible to soil water content than SWP. Therefore MDG and SWP can be used as a tool for irrigation scheduling.

4.3. Soil measurements

4.3.1. Soil variability maps using soil conductivity

Equipment used and operating principle of the measurement

The variability of the soil can be measured through conductivity (or its inverse: resistivity), and with a great number of measurements we can establish maps. Conductivity is correlated with several parameters of the soil. Two types of equipments can be used. The first is an electromagnetic induction (EMI) sensor, the second is an electrical resistivity sensor.

An EMI sensor measures the bulk electrical conductivity of the soil. A primary magnetic field that induces very small currents in the soil is generated by the EMI sensor, and then a secondary magnetic field is created. This secondary magnetic field is measured by a receiver coil in the sensor. Sensors are designed so that the secondary and primary magnetic field are linearly proportional to soil conductivity (Tisseyre *et Al.,* 2007). Two models are generally used in viticulture: the EM38 (Figure 24) and the EM 31 (Figure 25). The EM38 is the smallest model. When it is positioned horizontally, it can measure the conductivity from 0 to 75 cm depth. When it is positioned vertically, it can measure the conductivity from the 25 to 150 cm depth. The EM31 is longer but it can measure the conductivity at depth up to 3 meters. The measurement is easy to take: you have just to read the screen after placing the apparatus vertically or horizontally. But the apparatus needs to be calibrated quite often, and the operator has to take care not to measure close to metals objects, as trellis structures in the vineyard, because they can influence the readings.

The measurement has to be taken at the following vine growth stages: budburst, shoots 10 cm, flowering, or post-harvest.

Figure 24: EM38 ***(source : www.cflhd.gov).***

Figure 25: EM31 ***(source: www.geophysicalsurveys.com/utility/)***

The electrical resistivity sensor is actually a galvanometer with four electrode cells (Figure 26). The principle of this measurement is to artificially generate electric currents to the soil with two electrodes and then to measure the resulting potential differences with the two others (Samouëlian *et Al.,* 2005). This apparatus is used in precision viticulture for one-dimensional survey, called Vertical Electrical Sounding (VES). The electrical measurements are taken with different distances between the electrodes. The further the electrodes are, the deeper the measurement will be taken. The measurement is longer to be taken than with an EMI sensor, but there are less problems in vineyards because the trellis structure doesn't disturb the measurement. The measurement timelines are the same as the EMI sensors one: budburst, shoots 10 cm, flowering, or post-harvest. The survey spacing for a soil survey is determined by the level of detail required. But usually it should not exceed a width of 10 or 15m. To go faster, the sensors can be pulled behind a four-wheel motorbike (Figures 27 and 28).

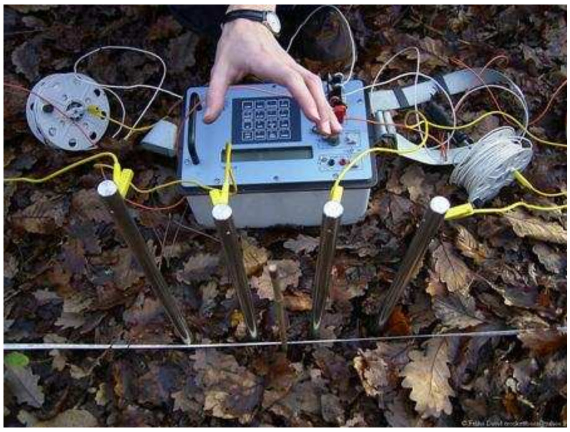


Figure 26: Resistivimeter ***(source: http://old. sciences.univ-tours.fr/geeac/moyens.htm).***

Figure 27: EM38 pulled behind a four-wheel motorbike *(source: Bramley, CSIRO).*

Figure 28: Resistivimeter pulled: Multidepth Continuous Electrical Profiling (MUCEP) *(source: Samouëlian et Al., 2005).*

Soil conductivity maps

Conductivity or resistivity measured by both apparatus are linked to several soil properties: nature and arrangement of solid constituents, water content, cation exchange capacity, pore fluid composition or temperature (Samouëlian *et Al.,* 2005).

Then, maps can be made to show the variability of the soil conductivity within the vineyard, and therefore the variability of the soils properties.

Figure 29 shows a soil electrical resistivity map, and similar spatial patterns with NDVI and trunk circumference (Figure 22) as it is the same vineyard. Therefore, the soil variability can be a good tool to zone the vineyard in high and low vigour zones.

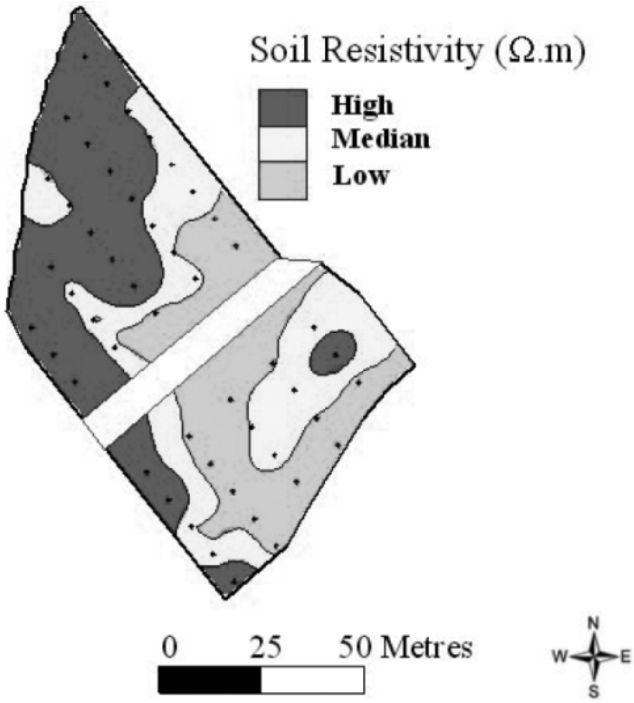


Figure 29: A map showing 3 classes of soil electrical resistivity (ohm.m) in a 1.2 ha vineyard of Syrah grapes in the Clape Massif, Southern France *(source: Tisseyre et Al., 2007).*

4.3.2. Soil temperature

This measurement consists in measuring the temperature of the soil at different depths, and during all the vine growth stages to see the influence of the temperature on the grape maturity.

The equipment used is a soil temperature sensor, such the one on figure 30, sold by Campbell Scientific®. This probe consists of a thermistor encapsulated in an epoxy-filled aluminum housing. The housing protects the thermistor allowing the probes to be buried or submerged. The sensor No. 107 measures from -35° to +50°C, so it is a good interval for soil temperature. The accuracy of this probe is inferior to ± 0.4°C.

Figure 30: Temperature sensor No. 107 sold by Campbell Scientific® (source: http://www.campbellsci.com/soil-temperature).

The operating principle is very simple. The probe should be placed horizontally at the desired depth to avoid thermal conduction from the surface to the thermistor. You can place the probe at different depths. Burgos *et Al.* (2007) measured the soil temperature at three different depths: 10 cm, 50 cm and 80 cm. The time required for each measurement is not very long, of the order of a few minutes. The sampling depends on the topography and on the soil type. If there is a big slope and/or different types of soil, more measurements have to be taken.

This measurement can be done at all the vine growth stages, from dormancy to post-harvest.

High soil temperature at 10 cm depth is correlated to the maturity of grapes (Burgos *et Al.*, 2007). Moreover, the number of days between bud and flowering, and between flowering and veraison decreases with a warm soil temperature: the maturity of grapes is accelerated.

Soils with a light texture and a high proportion of stones also showed lower levels of water and their temperature is warmer in the night, compare to loamy soils (Figure 31).

However, temperatures are nearly constant from 80 cm depth during all the vine growth stages.

These results can help winegrowers when they establish their vineyard and show that the soil environment plays a major role in development of the vine. The relationship between the water and soil thermal needs to be investigated to better understand and predict the evolution of the potential wine terroirs in relation with global warming.

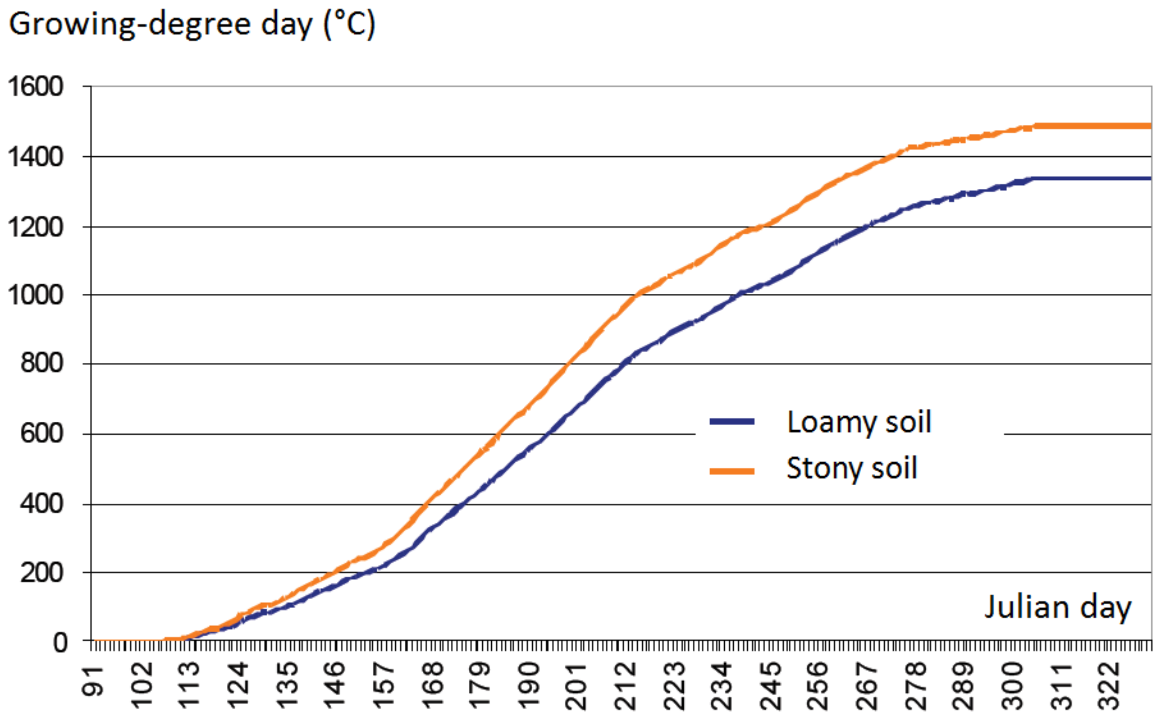


Figure 31: Growing-degree days at 10 cm depth in both types of soil *(source: Burgos et Al., 2007).*

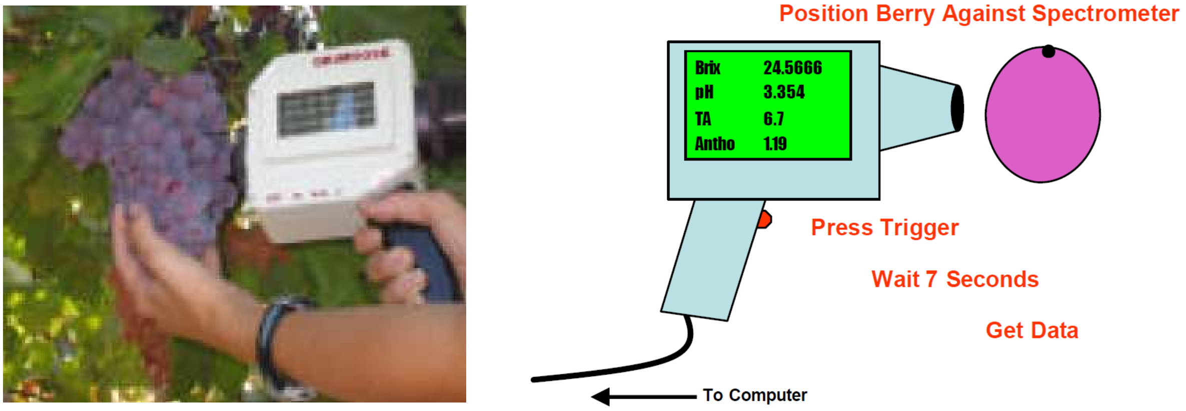
4.4. Quality measurements

The monitoring of quality parameters is harder to make because there are still no real-time harvester-mounted or hand-held sensors commercially available to measure quality parameters, such as Baumé and Brix, pH, Titratable Acidity (TA), anthocyanins or phenolics (Tisseyre *et Al.,* 2007).

But near-infrared (NIR) spectroscopy can be used to know the composition of the grapes. A NIR spectrometer (Figure 32) can take very accurate measurements compare to reference methods (Tuohy, 2005). Correlation coefficients are rather good for Brix, pH and TA between both methods (Table 1).

Table 1: Correlation coefficient between NIR measurements and reference methods for several calibrations *(source: Tuohy, 2005).*

Calibration	Reference Method	Correlation Coefficient
Brix	Refractometry	0.91
pH	pH Meter	0.75
TA (g/L)	Titration	0.76



(a) (b)

Figure 32: Photograph (a) and scheme (b) of a NIR spectrometer measuring several quality parameters *(source: Tuohy, 2005).*

4.5. Mechanic tools

To date, there are not many Variable Rate Technology (VRT) used in viticulture because Decision Support Systems (DSS), which permit to decide how much inputs to apply in a place, are not developed much. Therefore, VRT applications existing in viticulture are often simple, and lead to a direct fiscal benefit. But when DSS will be ready, VRT applications could be easily applied in viticulture as they are tried and tested in other agricultural industries

One of the main applications of VRT in viticulture is for the weeding operation (Tisseyre *et Al.,* 2007). A VRT weeding system is commercialized since 2003 to selectively apply herbicides: the Weedseeker from Avidor. This system is based on an optical sensor which measures reflectance at two wavebands (Green and NIR). The sensor detect the presence of

green weeds in the interrow or underneath the vine canopy (Figure 33 (a)) because the reflectivity of the chlorophyll is different from the soil one. Then, when the green weeds are detected, herbicide is sprayed (Figure 33 (b)). This system allows savings of up to 75% of herbicides (Chambre d'agriculture de l'Aude, 2005).

(a) **(b)**

Figure 33: Operating principle of the Weedseeker. (a) Detection of green weeds thanks to their reflectance. (b) Spraying of herbicides only on green weeds *(source: http://www.avidorhigh tech.com/html/weedseeker.html).*

The Weedseeker system can also be used on discontinuous vertical canopies to apply fungicides. In this case, the sensing system allows the spraying of fungicides only on the canopy, and not in the 'holes', there are less chemical products applied.

5. Current research and future developments

5.1. Yield sensors

Three yield sensors are available on the market, and three other are under development (Tisseyre *et Al.,* 2007). The first is developed by the Pellenc company (Pellenc S.A., Pertuis, France) specially designed to fit the Pellenc grape harvesters with onboard storage capacity. Another yield sensor is developed by a European project (Corea project), and as the latter is specifically designed to fit harvesters with onboard storage capacity. Finally, a third yield sensor is developed in Australia with the help of Precision Viticulture Research Group at the University of New England.

5.2. Soil properties sensors

5.2.1. Apparent electrical conductivity sensor

Figure 34: TDR sensor ***(source: http://www.envcoglobal.com).***

Two types of apparent electrical conductivity (ECa) sensors are mainly used: EMI sensor and electrical resistivity sensor. But a third sensor exists: the Time Domain Reflectometry (TDR) sensor (Tisseyre *et Al.,* 2007). Its commercial development for use on a mobile apparatus is being undertaken. TDR sensor works as a radar. A high frequency signal is pulsed down the probe. The reflection of this signal is proportional to the dielectric constant of the soil surrounding the sensor. The dielectric reading from the sensor is then converted to water saturation and transmits to the monitoring equipment. It provides reliable and accurate soil moisture monitoring. When installed vertically, the moisture sensor can be used to average moisture readings along a soil column. When installed horizontally, the sensor can be used to measure moisture at a specific soil depth.

5.2.2. On-the-go soil sensor

A new mobile on-the-go soil sensor is being constructed in USA and Australia to directly measure soil properties (Tisseyre *et Al.,* 2007). Other sensors are under development, including soil ion sensors (mainly nitrogen and potassium sensors) and Near-Infrared and Mid-Infrared sensing systems. Finally, ground penetrating radar and gamma radiometrics are trialed in viticulture to see if their use is possible.

5.3. Sprayer sensors

Spraying sensors has been mounted on sprayers of winegrowers in Nefiès (France), during the project Life Aware (Figure 35). There were sensors on the right and left sprayers, to measure the flows of pesticides sprayed, and one sensor in the sprayer to measure the volume of sprays remaining. A GPS was installed on the tractor, so maps could be produced, and a computer on board could inform in real-time the winegrowers about sprayers problems. Results of this project are optimistic, but efforts are to be made to make tools that can be use easily by winegrowers.

Figure 35: Sensors to measure the flow mounted on the sprayer *(source : http://life_aware.tele detection.fr).*

6. Conclusion

Tools used in Precision Viticulture are numerous and varied. Their use begins to be widespread in some countries, mainly in USA, Australia or New-Zealand. Even if their adoption in Europe has a bit delay due to traditions, their use will be soon very common.

These tools can provide very accurate information about all the characteristics of vineyards. Yield sensors, vigour maps using indices such as NDVI or PCD or soil sensing surveys are mainly used, but other interesting measurements can be made, such as trunk diameter or pruning weight. Quality measurements are not often used because there are still no real-time sensor commercially available, but research is doing in that way. As well, mechanic tools are few on the market, but tools exist in Precision Agriculture with other crops, so we can think that they could be used soon in viticulture. Intensive research is made in Precision Viticulture, and new tools are to be commercialized soon.

But these tools are not sufficient to do Precision Viticulture. Decision Support Systems have to be developed, because without them the commercial use of the PV tools is not possible. Some of the tools have to be simplified to be used by winegrowers. Finally, the social aspect has to be taken into account: the use of PV can bring about large effects on wine industry and winegrowers have to be better informed and trained.

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