MONITORING, MAPPING AND MODELLING THE VINE AND VINEYARD: COLLECTING, CHARACTERISING AND ANALYSING SPATIO-TEMPORAL DATA IN A SMALL VINEYARD

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Abstract

Precision Viticulture (PV) has potential to provide a range of environmental datasets, tools and techniques to collect, analyse and visualise data for vineyards over both space and time. As technology becomes more mobile, powerful, and accurate, and output easier to integrate, there is the capability to collect a wider variety of data about the vine plant and the vineyard environment. To date the use of PV in small vineyards has been relatively limited with many constraints preventing more widespread use. With the availability of low-cost and easy to use hardware and software PV is increasingly becoming a reality for the smaller vineyard operator. This paper identifies some of the more practical uses of geospatial technologies for smaller vineyards, and some of the benefits and limitations of the data, tools, and techniques available to yield information for vineyard management. The paper reviews the potential of PV for monitoring, mapping and modelling vineyards with a range of low-cost hardware, software, tools, and techniques. Case studies are used to exemplify the role of PV in small vineyards for the acquisition, processing, analysis and role of quantitative data describing the vineyard environment. For example, use of discrete measurements such as soil samples (pH and moisture) and continuous measurements such as DEMs and derivatives (slope, aspect, and curvature) including TPI (**T**opographic **P**osition **I**ndex), TWI (**T**opographic **W**etness **I**ndex), potential irradiation, and location. Analyses of attributes for the classification of different types of *Terroir* using aspatial cluster analysis, and Indicator Kriging with sample points to determine the most probable *Terroir* are also possible. Climate analysis is enhanced using basic agroclimatological indices (e.g. SAT, GDD) using the closest synoptic stations and for recommending vine varieties for different sites. The paper concludes with a summary of the benefits, issues and limitations of PV for the smaller vineyard.

Introduction

Precision Viticulture (PV) has rapidly become well established in the USA, Canada and Australia, and more recently in parts of Europe (e.g. Spain) and New Zealand. In the broadest sense, PV provides the means to collect, store, process, analyse, visualise and interpret a wide range of environmental datasets collected in the vineyard with the potential to better understand and account for the spatial and temporal variability observed in the plants and soils across the vineyard. More specifically it is the use of spatial (geography and location) and related technologies for the study of geographical variability in the vineyard as the means to provide a more objective basis for management practices.

The popularity of this approach to vineyard management has been aided by the availability of low-cost microprocessor technology coupled with cheap and easy to use hardware and software making the task of data acquisition and the processing of spatial data practical at the scale of the smaller vineyard, and without the need for specialist expertise. Until recently, however, most small vineyards were unable to make widespread use of PV because of the costs of the technology and expertise, as well as the steep learning curve required to make use of the data collected and the knowledge and skills required to analyse the data. However, this is changing and PV is now becoming increasingly popular and practical for the smaller vineyard operator. Publicly accessible meterological and climatological data is also proving beneficial as this can also be processed easily and combined with site data.

This paper briefly reviews the potential of PV for monitoring, mapping and modelling in the smaller vineyard with a range of low-cost hardware, software, tools, and techniques, followed by a number of case studies; examples designed to exemplify the practical role of PV. For example, use of discrete measurements such as soil samples (pH and moisture) and continuous measurements such as DEMs and derivatives (slope, aspect, and curvature) including TPI (**T**opographic **P**osition **I**ndex), TWI (**T**opographic **W**etness **I**ndex), potential irradiation, and location. Analyses of attributes for the classification of different types of *Terroir* using aspatial cluster analysis, and Indicator Kriging with sample points to determine the most probable *Terroir* are also possible. Climate analysis is enhanced using basic agroclimatological indices (e.g. SAT, GDD) using the closest synoptic stations and for recommending vine varieties for different sites. The paper concludes with a summary of the benefits, issues and limitations of PV for the smaller vineyard.

Precision Viticulture in the Smaller Vineyard

In many of the smaller vineyards most of the management practices such as planting, weeding, spraying, and picking are all usually very traditional in nature, and carried out by hand with the help of some small mechanical equipment such as rotavators and small-scale tractors. Furthermore, few of these vineyards have comprehensive and detailed records of their vineyard, let alone spatial information aside perhaps from a simple hand drawn map showing the location of blocks and varieties (Figure 1).

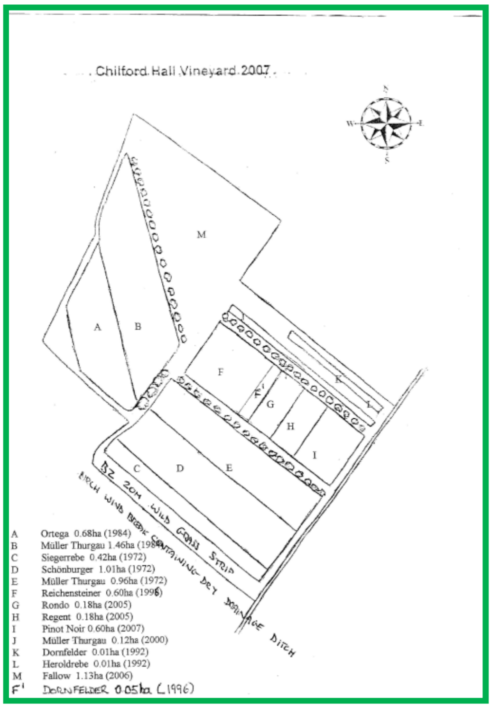

Figure 1 – Hand drawn map and record of a vineyard
(courtesy of Chilford Hall Vineyard, Linton, Cambridgeshire)

By comparison many of the large commercial vineyards make use of mechanical equipment guided by location-based technology e.g. Global Positioning Systems (GPS), acquire information from remotely sensed imagery, and use Geographical Information Systems (GIS) for mapping and databases. The value of using this often very costly technology is the economic benefit it brings to a commercial enterprise worth many millions of dollars each year. Wine is a very valuable commodity and in order to ensure growing the best grapes and production of the very best wine, high levels of investment are very important. PV has been most often associated with the larger commercial vineyards simply because smaller vineyards have not had the financial means to make use of the monitoring, mapping and modelling technology that is part of PV. Furthermore, the time to learn and make use of the technology has not been available. More recently, however, such technology has become cheaper to purchase, easier to use, and more practical to use.

Geospatial Technologies

There are a number of different technologies and applications that come under the heading of PV. Global Positioning Systems (GPS) are used to help navigate tractors around a vineyard guided by a GPS unit located in the driver's cab. GPS controlled equipment is also used to position the posts supporting the vine trellis, as well as vine plants during the planting of a vineyard, providing centimetre (cm) accuracy in the positioning and spacing of the plants and rows. In addition, GPS-guided equipment is used to help deliver doses of fertiliser, pesticides and herbicides exactly where they are needed in the vineyard as well as to prune vines and pick grapes. This particular technology can now be used to assist in many of the more traditional time consuming and backbreaking tasks in planting and managing a vineyard (Figure 2).

Figure 2 - Mechanised Grape Picking
(Harvest Pro Mechanical courtesy of Greg Kovacevich,Vineyard Ops. Inc., USA)

Besides using GPS units to control vineyard equipment, they also form the basis of accurately mapping a vineyard Such technology is now more user-friendly requiring minimal knowledge and expertise, and only requiring a shallow learning curve. One recent example is that of an Apple iTouch or iPad running the Cartographica App aided by the Bad Elf GPS unit (Figure 3). Maps collected in the field can be input into desktop software called a Geographical Information System (GIS). GIS provide a toolbox to input, manage and visualise or display both map and image data. Today there are many OpenSource examples of GIS software that can be downloaded from the Internet. Acquiring a GIS can provide the vineyard manager with an efficient way to manage the vineyard as well as generate informative graphics that can all be easily updated. With wine tourism becoming more important, having an accurate, detailed and professional looking map for display, on vineyard flyers, or the website is becoming important.

GIS also provides the means to create a vineyard database which can be used to store information, not only about what vine varieties are located where in the vineyard, but also information about the vine condition, the date of planting, as well as other useful information such as soil type and soil characteristics, the local geology, and information about grape yield amongst many other things (Figure 4). Such databases can be created in the GIS software or in a common desktop application such as MS-Office's Access or Excel.

Another interesting development is use of the freely available Google Earth (GE) software and the Internet. Both map and image data can easily be converted for display in this software, with the

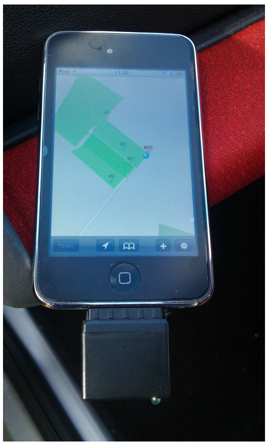

Figure 3 – iPod Touch running the Cartographica App and using a Bad Elf GPS unit

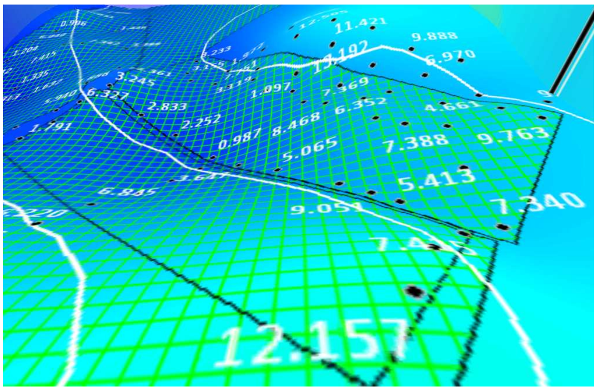

Figure 4 – Combining spatial information in a GIS
(soil moisture draped over a DTM)

possibility to add further information to the view and for generating fly-throughs or virtual fieldtrips. Amongst other things GE can be used as a simple GIS, and information can easily be added in the form of layers to overlay the GE imagery and to create simple visualisations of the vineyard terrain. Most GIS software now also allows the creation and export of GE files - known as KML (Key Markup Language) files - to GE.

Remotely sensed data in the form of aerial photographs and satellite images have been widely used for many years to provide up-to-date information about vineyards including soils, soil moisture and grapevine condition. The acquisition of low-cost photographic and digital imagery is now also possible with model aircraft and helicopters, as well as other larger UAV (unmanned airborne vehicles) something which enables the vineyard manager to obtain imagery virtually on demand. Besides colour aerial photographs, Colour InfraRed (CIR) imagery has become more widely available and can reveal useful information about vine health. Satellite imagery is used to derive information about the vine plant in the form of the Normal Vegetation Difference Index (NDVI). This requires the use of digital image processing (DIP) software; similar to graphics software used by photographers to edit photographs from digital cameras, DIP software can be used to extract information such as biomass and yield all useful to the vineyard manager. DIP software is also available for free on the Internet and can be used almost in a plug and play mode to extract information on a repetitive basis.

Besides the acquisition of data and information at the scale of the vineyard, PV also covers the acquisition of large scale data. For example, many vineyard managers require information about the microclimate of a vineyard. Useful measurements include minimum (MIN) and maximum (MAX) temperatures, light intensity, wind speed, and relative humidity (RH). Such measurements are helpful for optimising the management of the grape crop during the growing season. Today meteorological sensors are smaller, cheaper and can be operated in an automated mode, allowing data collection in multiple locations in the vineyard which can either be plugged into a computer using a USB cable or by taking advantage of wireless networks to relay information to a single computer in the manager's office. Many of these devices are now quite compact and come with software that configures the sensor, uploads the files, and displays the data in the form of a graph for ease of interpretation . When associated with a GPS location such measurements can be useful for examining and monitoring the variability of many different aspects of the vineyard microclimate which in turn can be correlated with the slope and topography of the vineyard site. Knowledge about the slope and aspect of a vineyard can be important for studying soil moisture and drainage, as well as cold air drainage; the effects of physical barriers e.g. tree shelterbelts and terracing, and channels e.g. ditches on cold air pooling and potential frost pockets, as well as maximising exposure to the sun for ripening the grapes. Site contours and 3-Dimensional terrain surfaces can be acquired from mapping agencies, or derived from aerial photographs using techniques known as photogrammetry. More recently, remotely sensed data such as LIDAR can provide detailed digital terrain models (DTMs) of a vineyard site as well as digital surface models (DSMs) showing the structures on the land surface (Figure 5)

Figure 5 – Mobile field data collection equipment

Most GIS have visualisation tools to display spatial information in the form of traditional looking maps or as 3-Dimensional terrain models which provide a feel for the topography of the site. Additional layers of information can easily be overlain on top of the topography which helps to provide insight into the relationships between the vines and the soils, soil moisture, air drainage, and exposure to the sun. As visualisation tools have become more powerful, realistic views of the vineyard can easily be displayed on a desktop or laptop computer, whether PC or Apple (including iPads) and used for further study or simply for a variety of communication purposes.

With the capability to acquire and display a wide range of data collected in the vineyard, more advanced uses of such information include the development of simulation models which allow one to create computer-based models of the vine plant and canopy. These can help to develop greater insight into growth and canopy development as well the sun, canopy, sun-shade relationships.

In addition to the growing capability to gather spatial data at the local level, publicly available meterological and climatological datasets now provide the basis for calculating additional information about a vineyard

Case Studies - Agroclimatological conditions in Chilford Hill and Camel Valley Vineyards

The following case studies have been included to highlight (a) the availability of other potentially useful and freely accessible data and (b) the ease with which such data can be utilised by the vineyard manager to generate useful spatially related agroclimatoligcal information relevant to the vineyard which has direct applicability in the context of location and management.. Case studies are presented to provide simple examples to illustrate for two study sites in the UK : Chilford Hall Vineyard in

Linton, Cambridgeshire, and the Camel Valley Vineyard in Cornwall, SW England, two well established but quite different UK vineyards (Figure 6). The resulting information is also compared to other sources of information e.g. an earlier study made by Cochrane (1974).

Case Study 1

A number of calculations were made based on gridded data acquired from the UK Climate Projections programme (UKCIP09). For each vineyard the data from the closest grid have been used (easting/northing coordinates in British National Grid coordinate system): 557500/247500 m for Chilford Hall and 202500/067500 m for Camel Valley.

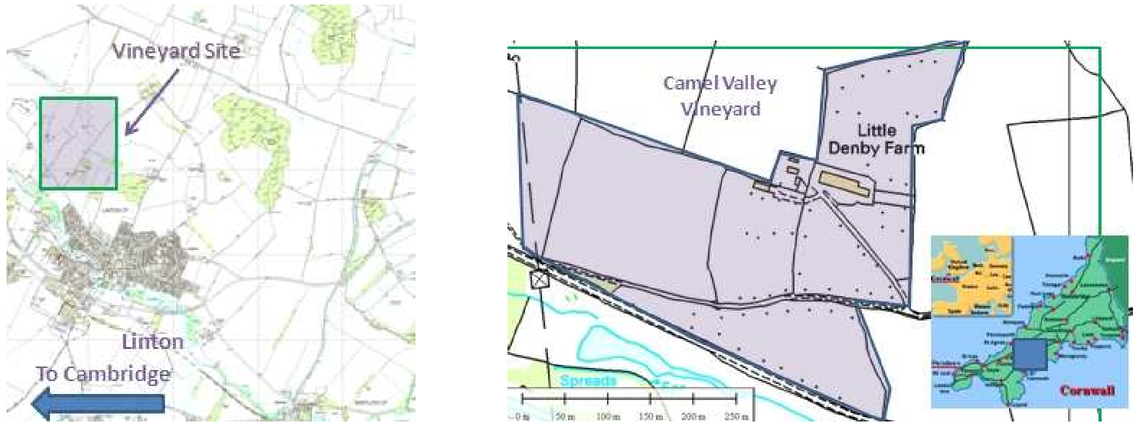

Figure 6 – Maps of Chiford Hall and Camel Valley vineyard study sites

a) Temperature statistics for the growing season (defined as April-October)

Table 1. Mean temperature of vegetation season in the period 1960-2006

Vineyard	Average	Max	Min
Chilford Hall	13.1	15.1	11.8
Camel Valley	13.4	15.1	12.2

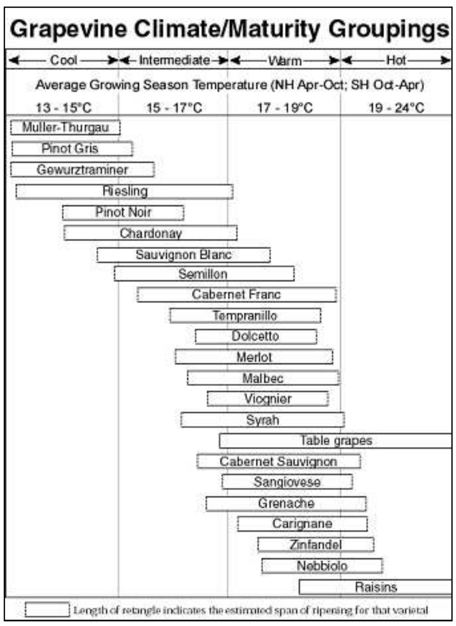

Figure 7. Mean temperature of vegetation season (April-October) (Jones, 2006)

Jones (2006) (Figure 7) shows that the mean temperature for the growing season in both vineyards limits the wine varieties that it is possible to grow.

Comparison of Figure 7 with the grape varieties grown (Table 2) reveals that for Chilford Hall and Camel Valley the following vine varieties are grown.

Table 2. Vine varieties grown in one vineyard or the other or both

Vineyard	CH	CV	Chilford Hall	Camel Valley
Varieties				Bacchus
			Dornfelder	Dornfelder
			Heroldrebe	
			Müller-Thurgau	Müller-Thurgau
			Ortega	Ortega
			Pinot Noir	Pinot Noir
			Regent	
			Reichensteiner	Reichensteiner
			Rondo	
			Schönburger	Schönburger
				Seyval Blanc
				Triomphe

b) Calculation of the Latitude-Temperature Index (LTI)

The Latitutde Temperature Index (LTI) is an index based on the latitude and mean temperature of the warmest month (T_{WM}) and is a proxy indicator of the amount of solar energy that areas are likely to receive during the growing season (Jackson and Cherry, 1988). LTI is quite often used to determine areas suitable for viticulture and to compare viticultural regions located at different latitudes (Jackson and Cherry, 1988; Gustafsson and Martensson, 2005). For these study sites, the mean temperature for July, usually the warmest month, has been used for the calculation of the LTI:

$$LTI = T_{WM} * (60 - latitude)$$

Based on this index, four climatic zones were distinguished for grapes cultivation (Table 3). For the two study vineyards both can be classified into zone A with an LTI of less than 190.

Table 4. Latitude-Temperature Index in the period 1960-2006

Vineyard	Average	Max	Min
Chilford Hall	130.3	162.4	130.3
Camel Valley	155.3	184.7	138.3

The preferred wine varieties for the LTI zones are shown in Table 3 below.

Table 5. Suggested groups of *Vitis vinifera* varieties according to Latitude-Temperature Index (LTI) and ripening ability in different climates (adapted from Gustafsson and Martensson, 2005)

Group	LTI	Varieties
A	< 190	**Bacchus**, Chardonnay, Pinot Blanc, Pinot Gris, Perle, Riesling and others
B	190-270	Pinot Noir and Riesling
C	270-380	Cabernet Sauvignon, Cabernet Franc, Malbec, Merlot, Sauvignon Blanc and Semillon
D	>380	Carignan, Cinsaut, Grenache, Shiraz, Zinfandel

The actual vines varieties grown in the two vineyards are shown in Table 2.

c) Sum of Active Temperatures (SAT)

SAT (the Sum of Average (Active) Temperatures) is the sum of mean daily temperatures equal to or higher than 10ºC for the period 1st Apr – 31st Oct (Jones and Davis, 2000). It is calculated as follows:

$$SAT = \sum_{1.04}^{31.10} \frac{T_{max} + T_{min}}{2} \qquad \text{for} \qquad \frac{T_{max} + T_{min}}{2} \geq 10°C$$

SAT is considered to be one of the most important thermal parameters in agroclimatology in general, as well as in viticulture. It is estimated that the SAT in a vineyard should be equal to or higher than 2500ºC. In fact, each variety has its own minimum average SAT value required during the growing season (Table 6).

Table 6. Average Sum of Active Temperatures (SAT) [°C]
and ripening ability of groups of varieties (Szymanowski et al., 2007)

Varieties	**SAT**
very early ripening	2000-2200
early ripening	2200-2500
moderately early ripening	2500-2700
late ripening	2700-2900
very late ripening	>2900

As can be seen from Table 7, Chilford Hall falls into the early ripening category, and Camel Valley into the moderately early ripening category.

Table 7. Sum of Active Temperatures (SAT) in the period 1960-2006

Vineyard	**Average**	**Max**	**Min**
Chilford Hall	2464.1	3033.1	1974.8
Camel Valley	2602.6	3101.7	2165.2

d) Growing Degree-Days (GDD)

GDD (Growing Degree-Days) is defined by the following equation:

$$GDD = \sum_{1.04}^{31.10} \frac{T_{max} + T_{min}}{2} - 10°C$$

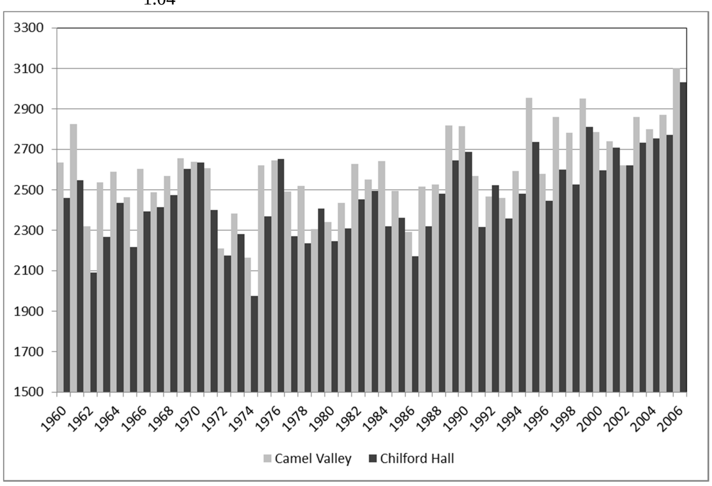

Figure 8. Sum of Active Temperatures (SAT) in the period 1960-2006

It is the summation of daily temperatures in the growing season (using a 10ºC base) to predict the vine's ability to produce a high quality crop in the northern hemisphere (Amerine and Winkler, 1944). Suitability models measure heat unit accumulation to ensure sufficient vine ripening. On this basis Amerine and Winkler (1944) divided the viticultural areas into five regions based on the GDD value (Table 8).

Table 8. Grape growing regions based on Growing Degree Days (Amerine and Winkler, 1944)

Region	**GDD [ºF] [ºC]**	**Suggested varieties**	**Type**	**Similar region to:**
I	≤ 2500 ≤1371	Early ripening varieties to achieve high quality	Very Cool	the coolest European districts such as Champagne in France and the Rhine in Germany
II	2501-3000 1372-1648	Early and mid-season table wine varieties	Cool	Bordeaux in France
III	3001-3500 1649-1927	High yield of standard to good quality wines	Warm	the Rhone in France or Tuscany in Italy
IV	3501-4000 1928-2204	High yield, but wine quality is only acceptable	Hot	the San Joaquin Valley
V	≥ 4000 ≥ 2204	High production of late season wine and table varieties for bulk production	Very Hot	only table grapes are usually grown commercially in this region

Table 9. Growing Degree Days s (GDD) in the period 1960-2006

Vineyard	**Average**	**Max**	**Min**
Chilford Hall	784.7	1143.1	534.8
Camel Valley	797.3	1111.7	530.3

Using this classification, both of the study vineyards should be classified into the very cool grape growing regions. In fact, for the cool climate growing regions like the German Rhine area, the GDD

Cochrane's 1974 study showed that for many vineyards in the UK the accumulated temperature sum falls well below 1000 degree-days at 750 degree-days. Cochrane (1974, p.144) notes that '*nevertheless, viticulture is practiced on a commercial scale in southern England and the distribution of existing vineyards can reasonably be accounted for by accepting a threshold value of 750 degree-days for standard meteorological exposure and relying on the advantages of a sheltered, sloping, southerly aspect and bare soil rather than grass to provide the extra 250 degree-days required*'.
equal to 944 was found as the lowest cumulative degree-day acceptable for commercial wine grapes (Table 10).

Table 10. Growing Degree-Days' suitability classes for cool climate growing regions (after Szymanowski et al., 2007)

Class	**GDD**	**Suitability**
1	> 1389	Most suitable
2	1165-1389	Good suitability
3	945-1164	Fair suitability
4	< 945	Questionable suitability

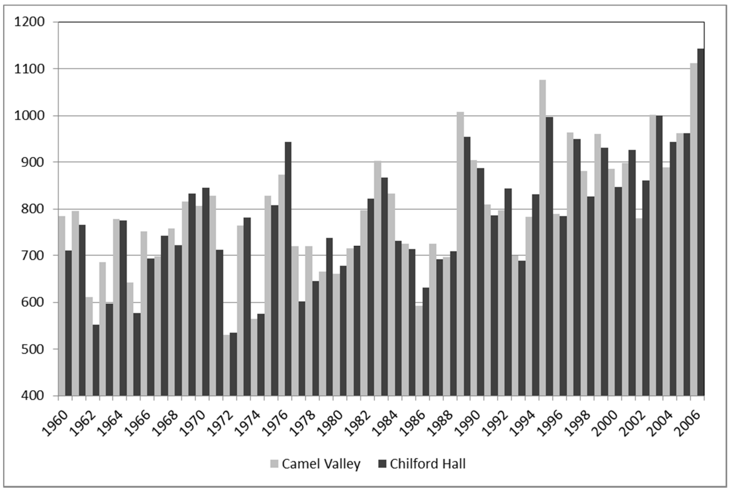

Figure 9. Growing Degree Days s (GDD) in the period 1960-2006

Case Study 2 - Cluster analysis

The next case study considers the use of a number of Digital Terrain Model (DTM) and Digital Surface Model (DSM) derivatives combined with field soil measurements such as pH and moisture to account for local microclimatic conditions observed in a vineyard. These include:

a) Sums of potential global solar irradiation in the vegetation period (Apr-Oct) [Wh^2m^{-1}]
b) Duration of incoming potential direct solar radiation [h]
c) Slope
d) Aspect
e) Curvature
f) Altitude above channel network
g) Topographic position index (TPI)
h) Topographic Wetness Index (TWI)

DTM & DSM heights and derivatives values were assigned to soil moisture data collected in the summer of 2011 for the two study sites. A K-fuction cluster analysis was performed to divide the entire dataset into three groups of points. The averages of the variables are shown in Table.

Table 11 Averages of the variables a-h

	Cluster 1 n=72 AVG	Cluster 2 n=16 AVG	Cluster 3 n=7 AVG
pH	8.8	9	9
Soil moisture	6.4	7.2	5.5
Altitude above channel	1.3	0.6	0.7
Curvature	0.1	0	-0.1
DTM	67.8	65.5	66.7
Duration of radiation DSM	2586.9	1693.2	874.5
Duration of radiation DTM	2907.6	2896.3	2894.3
Global radiation DSM	799175.1	620081.8	281606.1
Global radiation DTM	828112.4	822776	829406.3
TPI	0.1	0	0
TWI	6.9	7	6.9
Slope	3.1	3.7	3.5

Indicator kriging was used to determine probability of occurrence of each cluster type in each part of vineyard. A local raster function was used to determine sub-regions of vineyard.

The results of these analyses reveal that:

a) The vineyard is too small and is not subject to considerable variation or significant differences in conditions
b) Most diversifying factors are deemed to be of radiation origins e.g. differences of incoming solar energy and duration of insolation caused by the lines of trees planted around the vineyard.

Potential Benefits and Limitations

As the technology has become more practical and affordable PV has rapidly become a viable and affordable tool in the smaller vineyard. Naturally this precludes some of the more elaborate and expensive hardware and software found in the large commercial vineyards, but not the more affordable items described. Despite the potential of such technology, however, there are still limitations in terms of costs, the learning curve required, and the skills required to work with the technology.

As the case studies demonstrate, it is also easily possible to gather and process data and information about various aspects of a vineyard that can be used to provide the vineyard manager with a wide range of easy to derive and informative information to aid in aspects of vineyard siting and management. They also show that multiple sources of information derived from these widely available datasets can reveal new insight into where different vine varieties will grow successfully. Using only one piece of general information is not sufficient, and the location and success of a vineyard – especially in the UK – will be dependent upon many factors that can essentially buck the trend.

The availability of spatial data, and the developments in low cost geospatial tools and technique provides the means for vineyard managers to generate useful spatially related information for even the smallest vineyard site. This information has considerable potential in various different aspects of vineyard management, providing the basis for better and more informed decision-making at the site level, and the means to provide a baseline and record to map and monitor the vineyard over time.

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