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GIS, mechanistic modelling and ontology: a performing mix for precision and sustainable viticulture.

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Abstract. Precision viticulture has been developing very rapidly in the last two decades. Operational systems commonly use GIS, spatial interpolation, modelling, real time geolocalization, remote sensing and more recently, drone technology. Whereas precision viticulture is all about high space and time resolution of either measurements, analysis, diagnostics or decision support, few operational systems are built in an integrative way, combining many techniques and data sources. Within the European VINTAGE project, hourly time step climate data measurements, topography-based spatial interpolation, mechanistic soil, plant and disease models, remote sensing information and a decision support system are integrated within a GIS server to provide an operational tool for sustainable vineyard management for the grapegrower. The current study presents the overall system framework and first examples of model validation.

1 Introduction

Precision agriculture (PA) is a term now commonly used to address “that kind of agriculture that increases the number of (correct) decisions per unit area of land per unit time with associated net benefits” [1]. It therefore does not imply particular technology, but suggests that using methods increasing space/time resolution might be useful to enhance precision in farming techniques. Most of PA related literature focuses technology: high resolution and real time positioning systems (e.g. GPS), geographical information systems, variable rate technologies (VRT), and remote sensing techniques.

PA application to viticulture, hereafter referred to as PV (for Precision Viticulture) has been increasingly

developed since 1999 [2]. PA and PV research and commercial development has been consisting in a series of individual specific technologies such as yield measurement devices on harvester [3], light/radiometers for remote vegetation sensing (e.g. NDVI measuring devices [4]) or grape ripening estimates [5] coupled for positioning methods or techniques. Despite the recent rise of integrated systems such as multiple sensors combinations [6] or wide spatial coverage sensors [7][8], whole farm focus is lacking [1].

PA/PV are based upon innovative techniques. Their management and interpretation requires specific skills (e.g. programming, GIS management, image analysis, ...) that are sometimes far beyond the knowledge of the grower. An integrated acquisition and processing system

is therefore required to insure a relative autonomous use of PA systems. Modelling is necessary to translate raw data in either biological or agricultural information. This information might be then either directly used by the grower or interpreted by an expert before providing recommendations to the grower. Another possibility is to automatically process the final information via a series of decision rules. It avoids turning to an expert and it provides direct support to the final user. It is essential that the decision support, either automated or expert-based, use reliable source information to be elaborated.

In this paper, we present the current framework and features of VINTAGE, a decision support system (DSS) for integrating the management of the whole vineyard on a wine growing territory. The system, which development is currently being finalized, combines weather data, GIS information and modelling, plant, soil, grape disease models, decision rules and web services.

We evaluate the performance of VINTAGE via its plant model outputs on a pilot vineyard in Burgundy, France.

2 Material & Methods

2.1 The VINTAGE system

VINTAGE is an integrated system using precision viticulture to propose decision support to the grape grower. It is being elaborated within the VINTAGE project, an European Community (FP7) granted project involving a consortium of four European associations of grape growers (in Spain, Portugal, Italy and France) grouping several thousands of wine producers, two SMEs and six Research Transfer and Development Performers from Austria, France and Italy among Universities and Research Centers with specific expertise covering all the technical features required for the development of this system.

The consortium aims at developing an innovative management platform (including both software and hardware components) able to provide novel PV services to their associated members and to new clients. This platform makes available an easy to use web based software by means of which the end users (SMEs or Consortia of wine producers) have access to information needed to optimize their daily operations, including reports, statistics and in general way, all DSS outcomes.

2.1.1 Global framework

In the VINTAGE system (Figure 1), data derived from observation and analysis performed directly on the field, data automatically gathered by Wireless Monitoring Stations (WMS, weather and soil status monitoring) located on the field and data coming from satellites are received and collected in a common storage (database). These data are then processed by models and remote sensing (RS) sub-systems in charge of augmenting them by adding some additional derived indexes. These obtained augmented data are then used by the DSS engine to produce useful hints and suggestions.

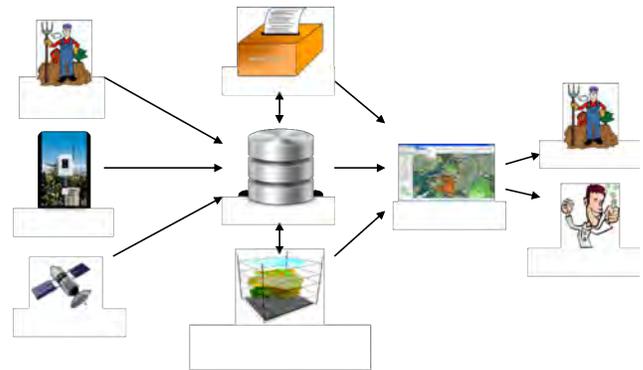


Figure 1: The VINTAGE global framework. WMS = Wireless Weather Monitoring Stations, DSS = Decision support system, HMI= Human Machine Interfaces.

A global picture of what's going on is offered to both final users and domain experts via a customized web GIS-like interface (VINTAGE front-end). By means of this front-end domain experts and final users are able to interact with the system in order to provide feedback and properly configure it.

Five macro feature/component blocks may be identified:

- WMS – Wireless Monitoring Stations (automatic source of data collected on the field)
- RS – Remote Sensing including Satellite Data and Image Processing (automatic or semi-automatic source of geospatial data)
- MOD – Soil, plant and phytosanitary models (input: field and geospatial data, output: soil, plant and phytosanitary indices)
- DSS – Decision Support System engine (input: models-augmented data, output: hints & suggestions)
- HMI – Human-Machine Interfaces (i.e. a web site and a smartphone application)

Each component has been implemented as a software service in the framework of a Service Oriented Architecture (SOA – a software architecture focused on

providing functionality through loosely-coupled software services). Each service contributes to reach the main goals of the system by operating in a set of defined sequences provided by a module tailored to coordinate them all (“orchestrator”).

Data coming from Remote Sensing, Wireless Monitoring Stations and direct observation by humans are acquired and collected by the system and categorized in: (i) parameter; (ii) field data; (iii) satellite data.

Parameters (i) are provided by humans and represent data such as user information (e.g. personal data, vineyard identification, etc.) and initialization data (e.g. plant density, grapevine cultivar, etc.). Field data (ii) are operative data (e.g. diseases symptoms, pruning, irrigation, etc.) provided by humans or as measures of physical quantities (e.g. temperature, humidity, etc) automatically acquired by WMS placed in the field. Satellite Data (iii) are EOS (Earth Observation System) data gathered from broadcast or satellite data providers.

Collected data is then elaborated to be spatialized (interpolated in space) and augmented resulting in: spatialized parameters (user information and initialization data available on the full grid of each Area Of Interest, AOI); spatialized field data (operative and measured data available on the full grid of each AOI); model indexes (specific geo-referenced indexes that simulate the current evolution of agronomical and weather related processes such as plant growth, soil physics and infection occurrences); remote sensing indexes (earth-surface variables and derived indexes useful in precision viticulture such as ones characterizing canopy structure, leaf optical properties, soil moisture, etc).

Data Mining techniques are used in an automatic form in order to provide context categorization and semantic tagging of data. Then starting from mined data overlapped with feedback coming from domain experts, a runtime environment will generate geo-referenced hints and suggestions.

An Integration Platform acts as a sort of glue providing common base services and functionalities such as shared data persistence management system, GIS-oriented commodities, a shared file-system, events management system.

Such a platform and each module are implemented in the form of a set of Virtual Machines (VM) in a virtualized networking environment in order to maximize modularization, scalability and flexibility of the solution. In this way the VINTAGE system may be easily deployed in many different shapes and sizes tailored to manage from a single vineyard to – potentially – the whole planet.

2.1.2 The Wireless Monitoring Stations (WMS)

Several agro-weather stations, conceived and installed in order to support the DSS, supplying detailed data to be used for model calculations/interpolations/validation (main and local stations) and reference for the selected area (main station). Custom electronics, able to control the whole system, is developed and built with special features, such as Solar panel plus battery recharge circuit on-board, smart remote reset by means of a simple phone call, remote firmware reprogramming, records backup and re-sending, in case of signal loss, acquisition and transmission intervals fully selectable, daily time auto resynchronisation, easy expansions with further sensors, IP65 and IP68 isolation.

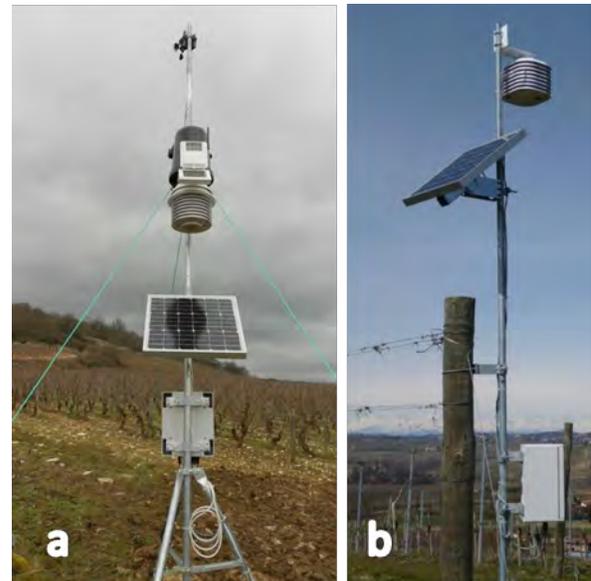


Figure 2: the Wireless Monitoring Stations (WMS). a: the main station in Saint-Romain (Burgundy, France) ; b: a local station in Serralunga d'Alba (Piemonte, Italy).

2.1.3 Interpolation procedure

Observed local weather WMS data are interpolated on an hourly basis over the domain. A Digital Elevation Model (DEM) is included as a proxy variable for the interpolation of air temperature and dew temperature. The DEM grid is also used as the base structure where data are interpolated and modeling computation is performed.

Meteorological variables are spatialized with procedures that combine classical smooth spatial interpolation algorithms (inverse distance weighting) and routines specifically devised for each variable [11]. Physical knowledge of specific spatial variability is incorporated, by choosing the right covariables that are

used to “detrend” original data, in order to eliminate the variability due to a geographic variable (e.g. elevation). The detrended data are interpolated by using classical smooth spatial interpolation routines, which take into account only their spatial statistical properties. Trends are then reintroduced at the end of this procedure on the interpolation grid. With detrending-retrending approach, the spatialization procedure allows to better explain both the local and the regional scales where atmospheric processes occur. This approach is applied for the variables which are mostly dependent on elevation: temperature and humidity.

For air temperature, an orographical analysis of thermal lapse rate is performed, using linear regression analysis and considering thermal inversions. Station data are detrended based on their elevation, using the modelled lapse rates. Detrended maps are produced over the domain and final temperature maps are obtained reconstructing the lapse rate over the domain grid using DEM.

For precipitation, a two-step procedure is applied [12]: a first interpolation, using only binary values (0 and 1) is performed to detect rainy areas, and a second one, using only positive observed values, to spatialize precipitation over these areas.

Relative humidity is interpolated by converting it to dew point temperature and using the same procedure as air temperature (detrending with elevation), then converting it back to relative humidity.

The components of the solar radiation budget at the surface (global, direct, diffuse and reflected) are computed on the DEM using the procedure described in [13]. Real-sky hourly irradiance for a horizontal surface is estimated using global transmissivity, computed as the ratio between clear-sky irradiance and interpolated global irradiance maps produced from the WMS data. A specific scheme adapted from [15] is used to separate beam and diffuse transmissivities and compute irradiances for inclined surfaces.

2.1.4 Soil, Grapevine and diseases models

The soil-water model is based on Criteria 3D (see a complete description in [13]) that solves the water flow equations in the soil, coupling a three-dimensional solution for infiltration and redistribution to an algorithm for surface runoff. This is obtained by means of an integrated finite difference scheme. The surface and sub-surface movement of water is fully coupled, using water head as state variable. Surface flow is described by the two-dimensional parabolic approximation of the St Venant

equation, using Manning’s equation of motion. Subsurface flow is described by the three-dimensional Richards’ equation for the unsaturated zone and by three-dimensional Darcy’s law for the saturated zone. The soil hydraulic properties are computed using the modified Van Genuchten- Mualem model proposed by [16]. Surface runoff on the lateral boundary of the domain and vertical free drainage in the last soil layer are the boundary conditions of the system. Precipitation, irrigation and root water uptake are sink-source at each node of the system.

The grapevine development and grape ripening is described through the coupling of different models which face the following features:

- Phenology;
- Leaf appearance and development;
- Photosynthesis.
- Berry ripening;

The phenological model is based on [17]. By means of two different thermal sums (ChillState and ForcState), calculated through chilling units and heat units respectively, the model describes the main phenological stages: endodormancy, ecodormancy, bud burst, flowering, fruit set and veraison. The thresholds over which a given phenological phase is reached were taken from [17] for Chardonnay and calibrated for the other varieties included in the project.

Unlike the original model, veraison phase was estimated through heat units as proposed by [18], consisting of the cumulated degree days calculated from March, 1st (for the northern hemisphere) onwards with base temperature set to 0.

In order to establish to best harvest time we developed a simple model which computes sugar concentration evolution starting at veraison. The sugar concentration (S) depends on ForcState, so that

$$ForcState(t) - ForcState(ver); S(t) < S_{max}$$

$$S(t) = 11.5 + 0.41 \cdot \frac{ForcState(t) - ForcState(ver)}{ForcState(ver) - ForcState(t)}$$

where $S(t)$ the sugar concentration of berries in °Bx on day t ; $ForcState(t)$ is the thermal sum on date (t). ver indicates the day of the year when veraison occurs (i.e. $t =$ veraison date) $S(t)$ has an upper bound given by:

$$S_{max} = 0.015 \sum rad + 5.21$$

where $\sum rad$ is the cumulated incident radiation from fruit set to veraison expressed in MJ.m⁻². Leaf appearance and development rate follow the model proposed by Bindi *et al.* [19]. From budburst, the shoot

leaf number (SLN) is determined by a first order differential equation involving only the daily mean temperature as environmental variable plus few empirical parameters. SLN is used to compute shoot leaf area and finally LAI.

The impact of water stress on leaf development was included by affecting the daily incremental rate by a factor dependent on the fraction of transpirable soil water (FTSW, see Eq. (2) in [20]). The above described models run at daily time step.

Plant growth is computed by simulating the photosynthetic process at hourly time step along the whole growing season. We implemented the scheme of the HYDRALL model [21], where plant canopy is simplified by means of the two-big leaf approach. Carbon assimilation is determined through the Farquhar equation [22] within an iterative procedure which computes at once stomatal conductance too [23]. Water stress acts in the process by reducing stomatal conductance as in [24]. We obtain then total biomass and water transpiration. Fruit biomass is determined by the total biomass following the approach in [19]. The necessary biochemical parameters for photosynthesis have been mostly taken from [25] and [26]. Beside the grapevine simulation we coupled a simplified growth model for grass based on light-use efficiency [27]. Scope of the latter is only to assess correctly the vineyard actual evapotranspiration.

Disease models are direct implementation of *Plasmopara viticola* (downy mildew agent) and *Erysiphe necator* (powdery mildew agent) mechanistic models described in [28] and [29].

2.1.5 Decision and Support System

By using the knowledge of fully-experienced experts, coded in form of a set of rules, an ontology-based artificial intelligence subsystem (DSS Engine) is in charge of integrating indices and estimations computed starting from satellite data, models and data coming from Wireless Monitoring Stations (WMS) in order to help users to take decisions. Hints and suggestions based on a large set of data, evidences, observations and best practice are provided to domain experts (e.g. agronomists) and final users (e.g. grape growers, winemakers, etc.). Three kind of key-information are generated: (i) what is suggested/recommended to do; (ii) list of facts that justify the suggestion (data, observations etc.); (iii) knowledge rules involved.

2.1.6 Human-Machine Interface

Results are displayed through an online portal, using web-GIS interfaces to visualize output as maps. The HMI are currently under development, and prototypes (Figure 3) are being tested by grape growers in the pilot areas, and by VINTAGE consortium members.

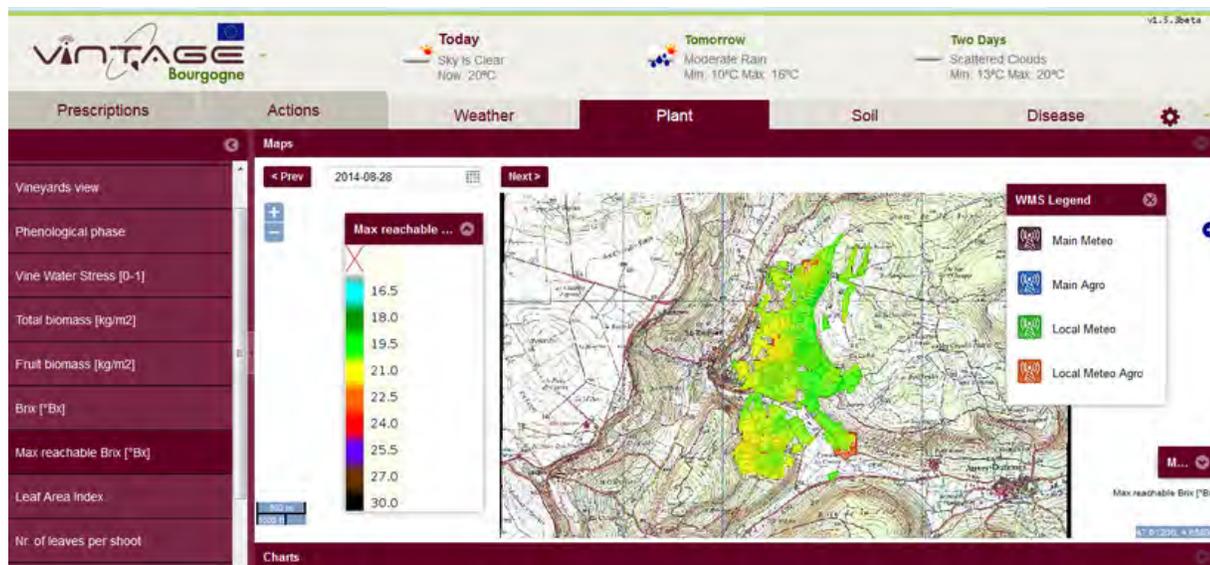


Figure 3: a screenshot of the VINTAGE beta interface.

2.2 Pilot vineyard in Burgundy

The VINTAGE system is implemented and tested in 4 pilot areas in Piedmont (Italy), Burgundy (France), Rioja (Spain) and northern Portugal. The current study focuses

on the work and validation performed in the Burgundy (France) pilot.

2.2.1 The study area

The French pilot area is located in Saint-Romain village vineyards (Burgundy, Figure 4). Saint-Romain is a protected appellation of origin appellation (AOP / AOC) of 97.5 ha of vineyards. Saint-Romain vineyards lies on three hillsides. Both of them consists in southeastern and southwestern oriented slopes of a north to south valley (Figure 4, top). This valley joins a larger east to west valley across which vineyards are planted on an east to north-east oriented hillslope (Figure 4, bottom). Vineyard soils have silty and clayey textures, with varying gravel contents. They are shallow calcaric-cambisols (from 0.3 to 1.5 meters depth) overlying late Jurassic limestones (top and lower part of the slope) and marls (mid to upper-slope).

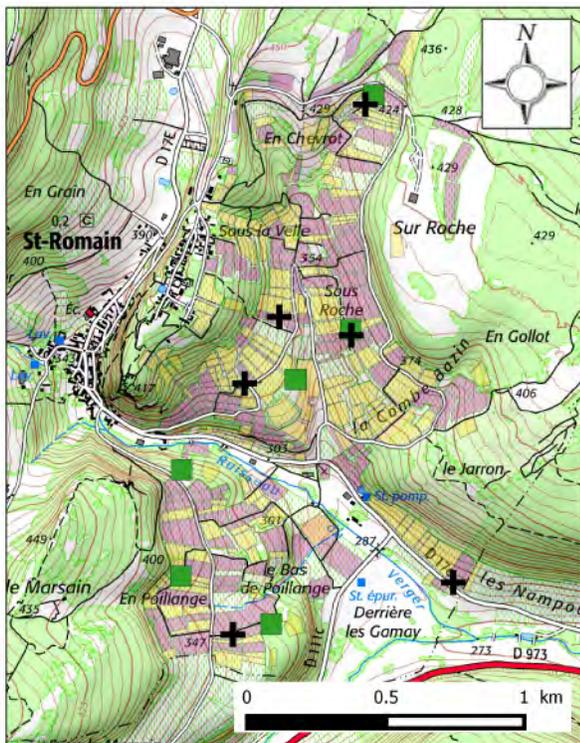


Figure 4: The Saint-Romain pilot vineyard. Source for the background map: IGN SCAN25[®]

2.2.2 Pilot WMS

Six Wireless Monitoring Stations (WMS) have been installed within the Saint-Romain area (Figure 4). A main station recorded temperature, humidity, rainfall, air pressure, global radiation, wind speed and direction. Five so-called “Local Meteo-Agro” stations measured air and canopy temperature, rainfall, leaf wetness and soil volumetric content at 30 cm depth.

The stations have been positioned in order to sample as much as possible the ranges in slope, aspect, soil features and above all, elevation.

2.2.3 Field measurements

During the 2014 growing season, data was collected in 6 experimental plots located in commercial vineyards of Saint-Romain appellation area (Figure 4,). Each plot was planted with *Vitis vinifera* cultivar Chardonnay. The training system was vertical shoot position (VSP) with simple guyot pruning, with one spur and an 8 buds cane. Plant spacing was 1 m between plants within the row and 1.1 m between the rows (9090 vines/ha).. The trunk height ranged from 0.35 to 0.45 m and the shoots were mechanically trimmed several times starting from early June at about 1.0 m to 1.2 m high. Soil was managed by tillage. Farming techniques differed from a plot to another, as they belonged to and were cultivated by different farmers.

For each plot, measurements were performed amongst 49 healthy vines. Starting from mid-May, phenology, leaf development, water status and fruit characteristics were monitored ().

Table 3: Saint-Romain (Burgundy, France) experimental plots

Location	Plot ID	Elevation (m).	Slope (°)	Aspect (°)	Terrain features	Soil
Perrière	PR	336 m	18.0	24	Midslope	Calcaric cambisol (Colluvic) on Nantoux limestone (mid to upper oxfordian)
Poillage haut	POH	357 m	10.7	122	Upper slope	Calcaric cambisol (Colluvic) on Saint-Romain marls (upper oxfordian)
Poillage bas	POB	329 m	5	30	Plateau	Calcaric cambisol on Nantoux limestone (mid to upper oxfordian)
En Chevrot	CH	419 m	6.1	158	Upper slope	Calcaric cambisol on Nantoux limestone (mid to upper oxfordian)
Sous Roche	SR	361 m	11.1	246	Midslope	Calcaric cambisol on Saint-Romain marls (upper oxfordian)
Sous le Chateau	SC	342 m	10.7	100	Midslope	Calcaric cambisol (Colluvic) on Nantoux limestone (mid to upper oxfordian)

Table 4: Grapevine field measurements

Measurement	Method	Acronym	Unit
shoot leaf number	Starting from May 15 to the end of August (8 sampling dates), 20 fruit shoots per plot (the most developed and the shortest one per vine, 10 vines per site) were measured in length, from the last opened leaf to the base, primary and lateral leaves were counted separately.	SLN	
Leaf area index	On 20 shoots per plot, the number of primary leaves (NL1) and the mean primary leaf area (M1) were used to estimate the mean primary leaf area per shoot according to Eq.(1) of Lopes and Pinto [30]. For secondary leaves the measurements started at the fourth sampling date. All lateral leaves were grouped into one dataset with the same type of variables as reported for primary leaves.	LAI	
Phenology	Mid-flowering (50% of the inflorescence at the BBCH stage 65) date, observed twice a week on 10 plants per plot	FLO	Day of the year
Grapevine water status	Midday stem leaf water potential measured as described in [31]	SWP	MPa
Berry composition	Sugar content assessed by IRTF analysis (uncertainty = 0.4°brix approx.), on the basis of 160 berries collected randomly on the 49 plants	SUG	°brix (g/100g of FW)
Berry weight	The average value of a berry weight estimated on 8 samples of 20 berries collected randomly on the 49 plants	BW	grams
Number of clusters per plant	Average number of cluster per plant measured on 8 plants at harvest	CN	
Number of berries per cluster	Cluster weight (8 plant at harvest)- bunch stem weight (measured on 520 grapes at harvest) divided by the average berry weight at harvest	BN	
Fruit biomass	Average berry weight multiplied by the number of berries at harvest multiplied by the number of clusters per plant multiplied by the number of plants per hectare divided by 10000 m ²	FB	kg/m ²

2.4 VINTAGE parameters and models assessment

The VINTAGE system was set up for each plot of the whole vineyard accounting to the cultivar. Training systems were considered similar in the whole area (no

custom settings were done by the growers). Indeed, Appellation of Origin specification are rather strict, and most of the vineyards have similar canopy geometry and plant density. However, pruning load might change from a grape grower to another.

As no soil map and analyses were available, the soils were considered as calcareous cambisol with homogenous features within the whole area.

Phenology, shoot leaf number, LAI, grapevine daily transpiration, grape sugar content and fruit biomass were extracted from the VINTAGE system at the experimental locations and compared to plot measurements.

3 Plant model evaluation

3.1 Growing parameters

In Saint-Romain, blooming occurred from June 7th to 10th (Figure 5). As field observations were performed twice a week, no clear difference between the 6 validation plots could be observed, except for the plot “EC”, located in the most elevated area, where flowering occurred the most lately, on June 10th. VINTAGE flowering date estimates were slightly biased (average difference of 2.57 days), which reduced the performance of the model (Root Mean Squared Error, i.e. RMSE = 2.72).

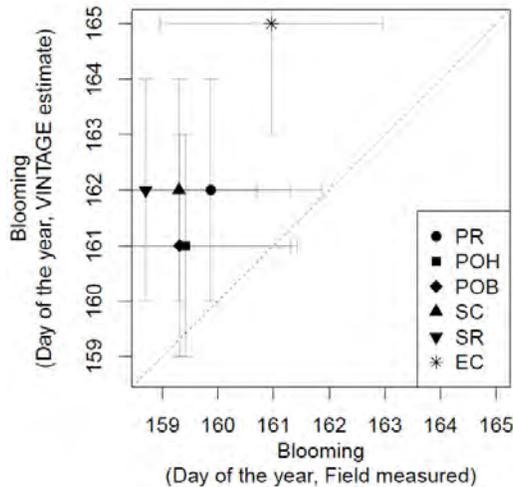


Figure 5: Flowering date estimates by VINTAGE. Error bars represent the 2 days estimated field measurement errors (as observations were performed twice a week). Each plot, flowering observations were made on 8 randomly selected plants. The solid line corresponds to the model perfect match (i.e. $f(x)=x$)

Leaf number estimates were far less accurate, especially after mid-June (Figure 6). Shoots were trimming during early to mid-June according to the farmers (plots). This operation was not filled within the VINTAGE system.

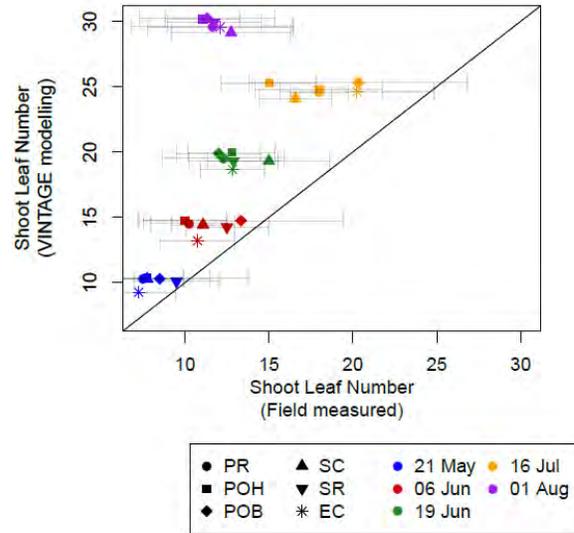


Figure 6 : Shoot leaf number estimates by VINTAGE. The solid line corresponds to the model perfect match (i.e. $f(x)=x$). The horizontal error bars are the standard deviations of the measurements (N = 20 for each point).

On May 21st, prior to shoot trimming, leaf number estimate is rather consistent with observations (RMSE = 2.16 leaves, Bias = 2 leaves). The plot “EC”, located at the highest elevation exhibits a slower development, as shown by the lower number of leaves both measured / estimated.

3.2 Fruit development

Fruit development was assessed by comparing VINTAGE fruit biomass output to both field measured berry weight and crop yield (i.e. fruit biomass).

Berry weight space and time variations followed globally the VINTAGE fruit biomass estimates (Figure 7).

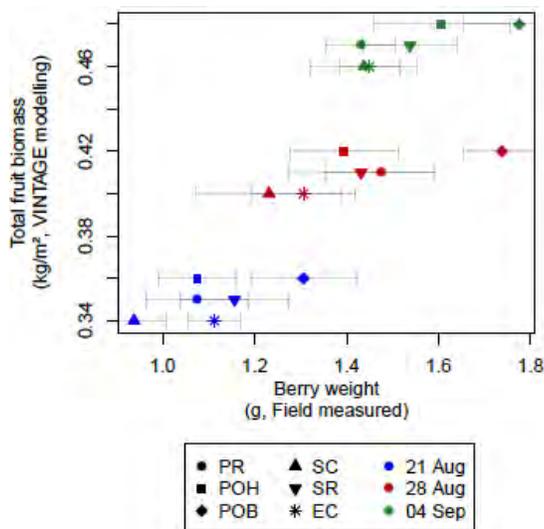


Figure 7: VINTAGE fruit biomass estimate vs measured berry weight. The horizontal error bars are the standard deviations of the measurements (8 weight measurements of 20 berries batches).

The steep south-exposed site “SC” had the lowest measured berry size, for 2 dates out of 3, and the lowest estimated fruit biomass. This might probably be due to higher water deficit experienced on this plot, as slope might enhance rainfall runoff and south aspect increases water loss by evapotranspiration enhancement by higher irradiation. In contrast, the highest measured berry weight and estimated crop was found in “POB”, a rather flat plot. Model estimates of the fruit biomass was not compared to the observed yield on each plot, because during the current experience, the VINTAGE system had not been configured accounting for pruning loading differences amongst the plots or crop thinning interventions, which might dramatically.

VINTAGE underestimated sugar content in grapes (biases of -0.45° , -2.45° and -3.27° for August, 21st, August 28th and September 4th). However, it captured rather accurately the spatial variability in sugar, for the last two measurements (Figure 8, $R^2 = 0.62$ and 0.77 for late August and Early September measurement). This suggests that VINTAGE might be a useful tool to estimate the harvest order of plots within the vineyard. On the contrary, more efforts in improving accuracy (i.e. bias reduction) is needed to make VINTAGE useful for targeting maturity control or harvest for the whole vineyard.

Success in capturing the spatial variability of sugar content is unexpected as plots used to evaluate the model outputs belonged to different farmers. It could have been

expected that changes in farming techniques (not accounted for by VINTAGE) would have affected greatly grape ripening. For example, leaf/fruit ratio control, a crucial parameter for grape maturation [32], changes probably from a plot to another (though not measured during 2014).

In this specific case, therefore, the climate local variability as well as terrain characteristics, might have been the largest guiding variable for sugar content determination.

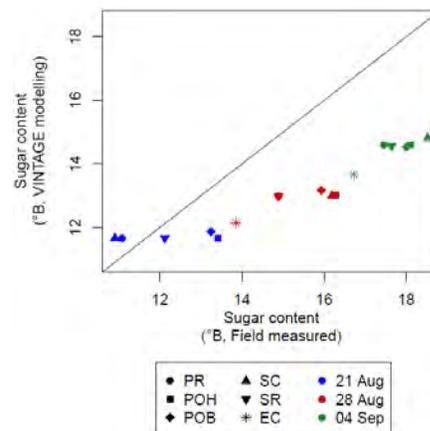


Figure 8. Sugar content estimates by VINTAGE. The solid line corresponds to model perfect match (i.e. $f(x)=x$).

4 Conclusion

Like many industries, agriculture has undergone profound changes since the industrial revolution starting from the late 19th century. Current issues in agriculture are mostly on optimizing yields, while developing environment friendly practices [7]. The specificity of viticulture lies in the requirements with respect to the final product quality. The latter is largely dependent on both abiotic environment (i.e. soil, terrain and climate) and cultural practices. Most operational services provided by precision viticulture concern only one of those aspects: enhancing yield or quality or reducing the environmental footprint of farming techniques. The VINTAGE system, however, has the ambitious goal to simultaneously meet these demands while providing greater comfort to grape grower. To successfully achieve this challenging aim, it combines climate and soil ground-based measurements (WMS), remote sensing, plant, soil and disease modelling, GIS and decision rules. The current evaluation of the plant model, yet preliminary, suggests that spatial accuracy and precision cannot be reached without an accurate description of farming techniques applied to each plot.

However, the spatial diversity of the climate and terrain features accounted for in the current experiment seem to contribute strongly to grapevine phenological timing, berry development and berry sugar content.

Further evaluations are in progress, including field data collected in other pilots, as well as improved plant modelling and comparison between the DSS recommendations and the farmer practices.

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